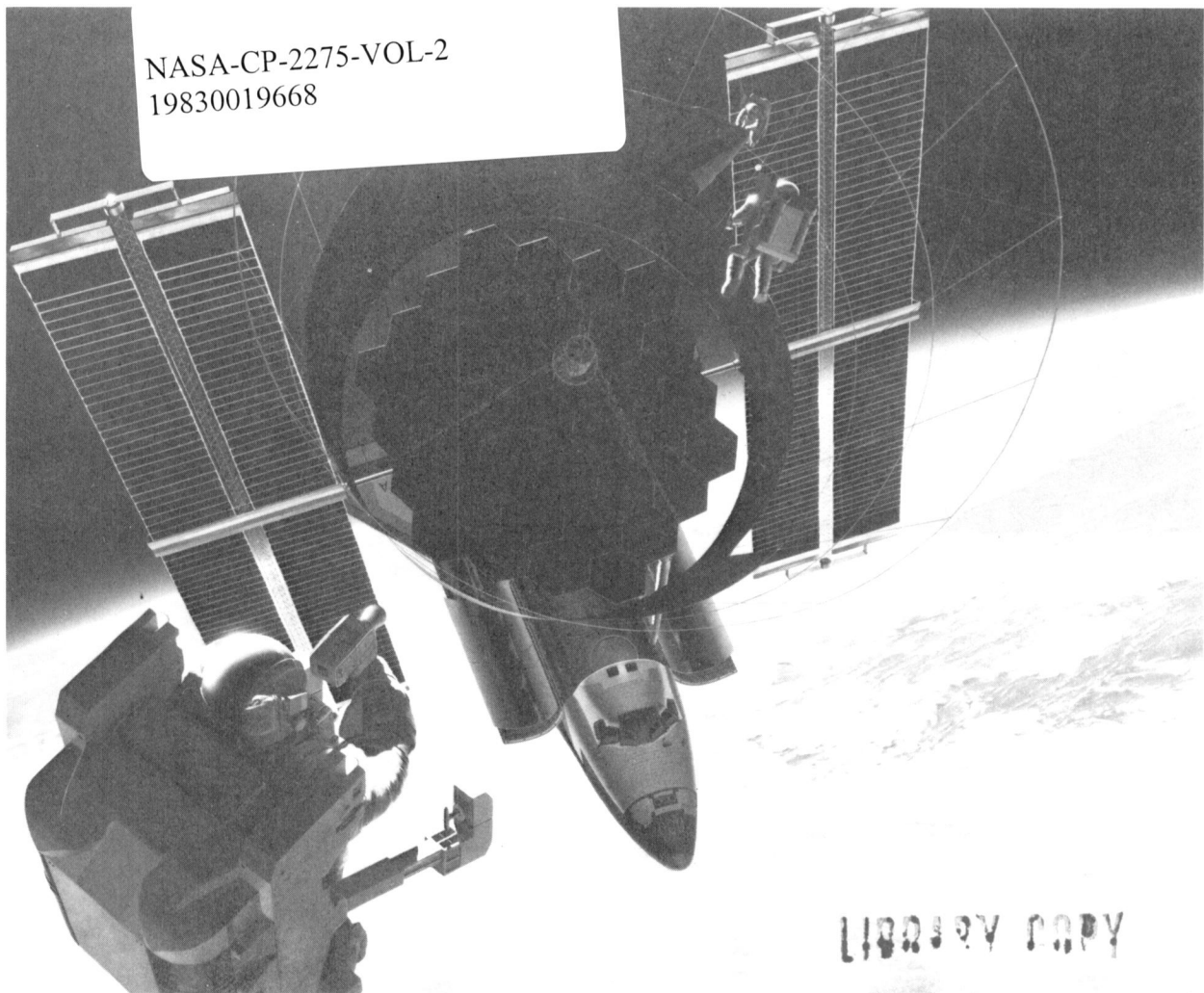


Large Deployable Reflector Science and Technology Workshop

Volume II—Scientific Rationale and Technology Requirements



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Asilomar Conference Center
Pacific Grove, California
June 21–25, 1982

NASA
National Aeronautics and
Space Administration

Large Deployable Reflector Science and Technology Workshop

Volume II—Scientific Rationale and Technology Requirements

Asilomar Conference Center
Pacific Grove, California

June 21-25, 1982

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Space Administration

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PREFACE

This report describes the scientific results of the meeting held on June 21–25, 1982 at Asilomar, California and sponsored by the National Aeronautics and Space Administration (NASA) to evaluate the prospects for astronomy of the Large Deployable Reflector (LDR), a submillimeter/far-infrared telescope which is projected to fly in space in the 1990s.

This report is volume two of three volumes which recorded the proceedings of the NASA LDR Science and Technology Workshop. Volume one is the Executive Summary and volume three is the Technology Report.

Approximately 40 astronomers attended, most of whom participated in both the science evaluation and the parallel technical evaluation sessions. The basic material for this report was generated by these science workshop members listed in appendix C.

Special acknowledgments go to the LDR workshop overall chairman, W. J. Welch, to the science chairman, T. Phillips, and to the panel chairmen, E. Wright (Cosmology), G. Wynn-Williams (Extragalactic and Galactic Structure), S. Strom (Stellar Evolution), N. Evans (Interstellar Medium), and A. Tokunaga (Solar System) for generating supplementary material and for editing in the post workshop period.

I am particularly grateful to N. Evans, E. Wright, and M. Werner for considerable help in various drafts of this report. T. Kuiper, D. Gilman, S. Gulkis, and J. Burke provided valuable criticisms and comments, and J. Carr generated useful sensitivity plots.

Finally, a special thanks should be given to Mike Kiya and Bill Gilbreath for their successful efforts in bringing the LDR workshop into being, and to Frank Fiore and Bruce Baumrucker of Vectors Unlimited for administering the workshop and compiling the three volumes of this report.

D. Hollenbach
NASA Ames Research Center
October 29, 1982

PREAMBLE

S. Strom
LDR Workshop
June 25, 1982

It is occasionally difficult for many of us, certainly for me, to achieve a proper perspective on astronomy in space in an era when the harsher aspects of the real world of budgets and priorities clash with the expansiveness of one's scientific dreams.

However, let us reflect for a moment on the epoch of exploration and discovery which is about to begin. America, through the National Aeronautics and Space Administration will, over the next two decades, place in space instruments of potential significance unparalleled in the history of science.

The Space Telescope will establish the distance scale to the galaxies and possibly the geometry and eventual fate of the universe. This pioneering observatory in space will tell us much about the evolution of galaxies and the engines which produce the incredible levels of energetic activity at their centers.

The Advanced X-Ray Astrophysics Facility will permit us to view the universe of high-energy phenomena. With AXAF, we will probe the temperature, density, and chemical composition of the gaseous medium which pervades clusters of galaxies. We will witness material as it approaches the edge of supermassive black holes and "listen" to quakes on the surfaces of extraordinarily dense, dying stars. We will be able to observe matter under conditions far beyond the limits of temperature and density achievable in earthbased laboratories.

The Large Deployable Reflector offers the promise of learning how diffuse matter in the cold depths of dark clouds is assembled into stars and solar systems and possibly how and when matter assembled into galaxies and clusters of galaxies not too long after the "big bang."

I am compelled to recall President Kennedy's speech nearly 20 years ago at Amherst. He reminded Americans at that time that the measure of a civilization was not to be found in the strength of its armies or its economy — important as they are — but rather in the vigor of its intellectual life as expressed in the visions of its poets and indeed its scientists.

I can imagine no more eloquent expression of the best in American civilization than the will to accept the challenge and possibilities of building and launching ST, AXAF, and LDR. Indeed, I doubt we could will a grander legacy to succeeding generations of scientists.

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I. INTRODUCTION

A. GENERAL OVERVIEW

The Large Deployable Reflector (LDR) (see fig. I.1) will be an orbiting telescope of 20 m diam, constructed by novel technologies. The deployment of this large, high-precision antenna in space will provide scientists with a powerful new tool for studies of far-infrared and submillimeter radiation. LDR will study newly forming stars and planetary systems with unprecedented precision. LDR will also detect the ancient, red-shifted signals from galaxies, galaxy clusters, and pregalactic gas located at the very edge of the universe.

Over the past two decades, exploratory satellites and, more recently, fully equipped space observatories have permitted the study of several regions of the electromagnetic spectrum not available from the surface of the Earth. In combination with optical and radio information, obtained by the concerted efforts of generations of astronomers working from the ground, the new data have helped to reveal a picture of the universe which reflects the full richness of its varied and beautiful phenomena. The extensive wavelength region between 30 μm and 1 mm, known as the far-infrared (30 to 200 μm) and submillimeter (200 μm to 1 mm),¹ has yet to be explored, in part because the obscuring effects of the Earth's atmosphere confound efforts to observe such radiation (except in narrow, variably transmitting windows (see fig. I.2). Most of the gas and dust in space radiate primarily in this wavelength band which is therefore of great importance for the study of many crucial astronomical problems. Far-infrared (far-IR) and submillimeter radiation carries information vital to the decoding of the structure of the youngest forming stars and of the coldest and most red-shifted objects in the universe.

Stars and solar systems begin their lives in the cold depths of optically opaque clouds of dust, atoms, and molecules. At far-IR, submillimeter and radio wavelengths, these clouds are transparent and feeble radiation within them can be seen and studied by telescopes of sufficiently great size and sensitivity. Only a fraction of the radiation from star-forming regions is emitted at radio wavelengths, and therefore, large, ground-based radio telescopes have limited sensitivity to such sources. Thus, a large instrument such as LDR, operative in space at far-IR and submillimeter wavelengths, is essential in order to observe the physical and chemical processes which are necessary precursors to coalescence of this material into protostellar units. With LDR we will, for the first time, be able to witness the growth of sun-like stars and to learn whether the formation of planetary systems is a necessary result of stellar births.

LDR will also permit us to observe the fluctuations in the cosmic background radiation. These highly red-shifted signals from the first matter to decouple from the "primordial soup," hold the key to understanding how the universe achieved its curious state and contain information concerning the nature and evolution of embryonic galaxies. Also, the evolutionary fate of the universe may be learned from study of the cosmic background radiation as it interacts with the enormously hot, diffuse material which pervades rich clusters of galaxies. From temperature measurements made with a precision of one part in a million we can determine whether matter in the universe will continue to disperse or eventually slow down and contract to a singularity, perhaps to begin the evolutionary cycle.

LDR will be a major component in NASA's long-term commitment to place in space, permanent, orbiting astronomical observatories that are sensitive to radiation over the full range of the electromagnetic spectrum. Over the next decade, NASA expects to launch the Space Telescope (ST), the first large, permanent

¹The precise wavelength range of the far-infrared and submillimeter has traditionally been ill-defined. We take these arbitrary ranges for our working definition.



Figure I.1.— An artist's conception of a shuttle-deployed LDR.

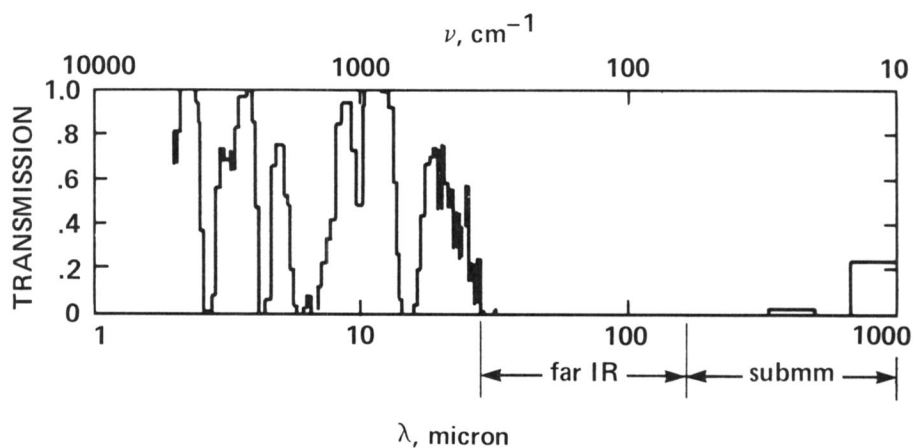


Figure I.2.— The atmospheric transmission from $1\mu\text{m}$ to 1 mm at an altitude of 4.2 km , representative of the best from a mountaintop observatory. The band pass varies from 5 cm^{-1} to 100 cm^{-1} to keep the resolution on the figure roughly constant. Most of the absorption over this band is due to water vapor; a column density of 2.4 precipitable millimeters is assumed.

optical/ultraviolet orbiting observatory. ST should provide the necessary observations to establish an accurate distance scale for the universe and to chart the evolutionary history of galaxies.

Later, the Advanced X-Ray Astrophysics Facility (AXAF) will permit the panoply of high-energy phenomena in the universe to be studied. The hot gas pervading clusters of galaxies, the plasma entering supermassive black holes in galaxy centers, and the signals from starquakes on superdense stars will all be observable with AXAF.

Among this complement of extraordinary observatories, LDR represents a significant departure in design and philosophy. LDR will be the first astronomical observatory to be erected and assembled in space, a distinction that brings with it major challenges to current technology. At the same time, achieving LDR objectives will provide invaluable experience in the art of constructing high precision, large space structures.

The benefit of bringing this new art into the service of astronomy and mankind's other endeavors cannot be calculated. The results of the LDR workshop at Asilomar, summarized in this document, represent the first stage in a continuing effort to define the scientific possibilities and the engineering requirements of this next-generation space structure and to meet the challenge of constructing this new eye on the universe.

B. HISTORY OF LDR

The impetus for the development of the LDR began in the late 1970s with two parallel proposals — one for study of a large submillimeter telescope by the Jet Propulsion Laboratory, and the other for study of a large (IR) telescope by the Ames Research Center. These proposed studies were united into one project intended to lead to the development of a large-aperture (at least 10 m effective diam) telescope for far-IR and submillimeter astronomy.

Discussions with university scientists and representatives of aerospace companies working on related problems indicated that such a telescope would be technically feasible in the 1990s; this conclusion was reinforced by technical studies sponsored by NASA. Even at this early stage in its definition, the LDR was among the projects reviewed by the Astronomy Survey Committee of the National Academy of Sciences. This committee, which was charged with defining a program of astronomical exploration and study extending well into the 1990s, recommended LDR with high priority as a major new NASA Space Program for development in the late 1980s, saying:

“The Astronomy Survey Committee recommends the construction of a Large Deployable Reflector of the 10 m class in space to carry out observations in the far-infrared and submillimeter regions of the spectrum that are inaccessible from the ground. A number of important scientific problems are uniquely accessible to such a Large Deployable Reflector in space. For distances less than 500 parsecs, the projected beam diameter will be less than 1000 AU.

“Direct measurements of the sizes of nearby clouds collapsing to become stars will thus be possible at far-infrared wavelengths, which can penetrate the surrounding clouds of dust that invariably obscure small-scale features at optical wavelengths. In addition, the wavelength regions accessible to an LDR contain spectral lines of atoms, ions, and molecules that reflect a wide range of astrophysical conditions.

“Studies of these features will yield otherwise unobtainable information about the structure and dynamics of planetary atmospheres; the heating, cooling, and chemical composition of the

interstellar medium; and, because of the penetrating power of long-wavelength radiation, chemical abundances in the highly luminous, but optically obscured nuclei of active galaxies.

“The sensitivity and high angular resolution of an LDR will also make it possible to study newly forming stars in optically obscured regions of nearby external galaxies, enhancing our understanding of galactic evolution and of the dynamical processes that stimulate star formation. Such an instrument can also probe the structure of the early Universe and the mechanisms of galaxy formation through studies of small-scale spatial fluctuations in the cosmic microwave background radiation.”

It is anticipated that the LDR will be a major national project with far-reaching astronomical and technical ramifications. The Asilomar workshop made the first major attempt to define the scientific rationale for the LDR and to compare the astronomical requirements with the technical possibilities. The large number (~ 100) of scientists and technologists involved in the workshop and the wide range of topics discussed are evidence of the excitement and challenge of this project.

II. OVERVIEW OF CONCLUSIONS OF SCIENCE WORKSHOP

A. HIGHLIGHTS OF LDR SCIENCE

Viewed in the broadest sense, the scientific rationale for LDR outlined in this document imposes two crucial instrumental requirements: angular resolution approaching 1 arcsec in the $2\ \mu\text{m} - 100\ \mu\text{m}$ wavelength region and high-resolving-power spectroscopy with good sensitivity. This reflects the historical experience in the optical and radio wavelength bands where imaging and spectroscopic capabilities brought a new dimension to our understanding of the universe. These two themes recur throughout the range of scientific problems discussed below.

Before delving into the detailed discussions of scientific problems, it will be helpful to obtain a broad view by considering the capabilities of LDR in juxtaposition with the range of scientific problems to be addressed. In figure II.1 the typical sizes of objects that LDR will study are indicated, as well as the distances at which they are likely to lie. Two diagonal lines indicate angular resolutions of 30 arcsec, about the best achievable with the Kuiper Airborne Observatory (KAO) and the Shuttle Infrared Telescope Facility (SIRTF) in the far-IR ($\lambda \sim 100\ \mu\text{m}$), and of 1 arcsec, the desired resolution for LDR in the IR. It can be seen that 1 arcsec will allow us to resolve and study in detail a number of objects ranging from distant galaxies, to spiral arms in distant galaxies, to giant molecular clouds (GMC) in nearby galaxies, to the collapsing precursors of protostars in our own galaxy, and, perhaps, to planetary systems around nearby stars.

In addition to the objects shown in figure II.1, planetary features such as the bands and the Great Red Spot on Jupiter can also be resolved by telescopes having 1 to 5 arcsec resolutions. The reasons why it is necessary to resolve these objects are detailed in the following sections, but it is clear that LDR, with angular resolution of 1 arcsec, will bring into much sharper focus our view of the universe at IR wavelengths.

The second major theme for LDR will be sensitive observations of spectral lines. The region from 1 to $1000\ \mu\text{m}$ is crowded with spectral lines of important molecules, atoms and ions, some of which are listed in figure II.2. These lines can be used to probe the physical, chemical, and dynamical conditions in objects as diverse as giant molecular clouds in external galaxies and comets within our own solar system. The critical role for LDR in this area arises from its large collecting area which allows the detection of very weak lines in small ($\lesssim 1$ arcsec) sources, and from its ability to accommodate the complex instrumentation required for spectroscopic observations.

LDR is essential for investigating a wide range of scientific problems detailed in Section III; here we highlight part of the scientific rationale for the LDR. The two areas where LDR will have the greatest impact, as anticipated by the Astronomy Survey Committee, are in studies of the formation of stars and planetary systems and in studies of the structure of the early universe. We conclude by summarizing the major telescope requirements derived from the scientific rationale.

1. The Origin and Evolution of Stars and Planets

Understanding the physical processes which control the formation of stars is one of the fundamental challenges of modern astrophysics. Stars form in condensations of gas and dust within the giant molecular clouds which pervade the disks of galaxies. It is thought that the collapse of these condensations under their own self-gravity leads to the formation of prestellar disks from which stars and planets are born, a process marked by increasingly complex cosmic chemistry which may ultimately produce the basic molecular prerequisites for life.

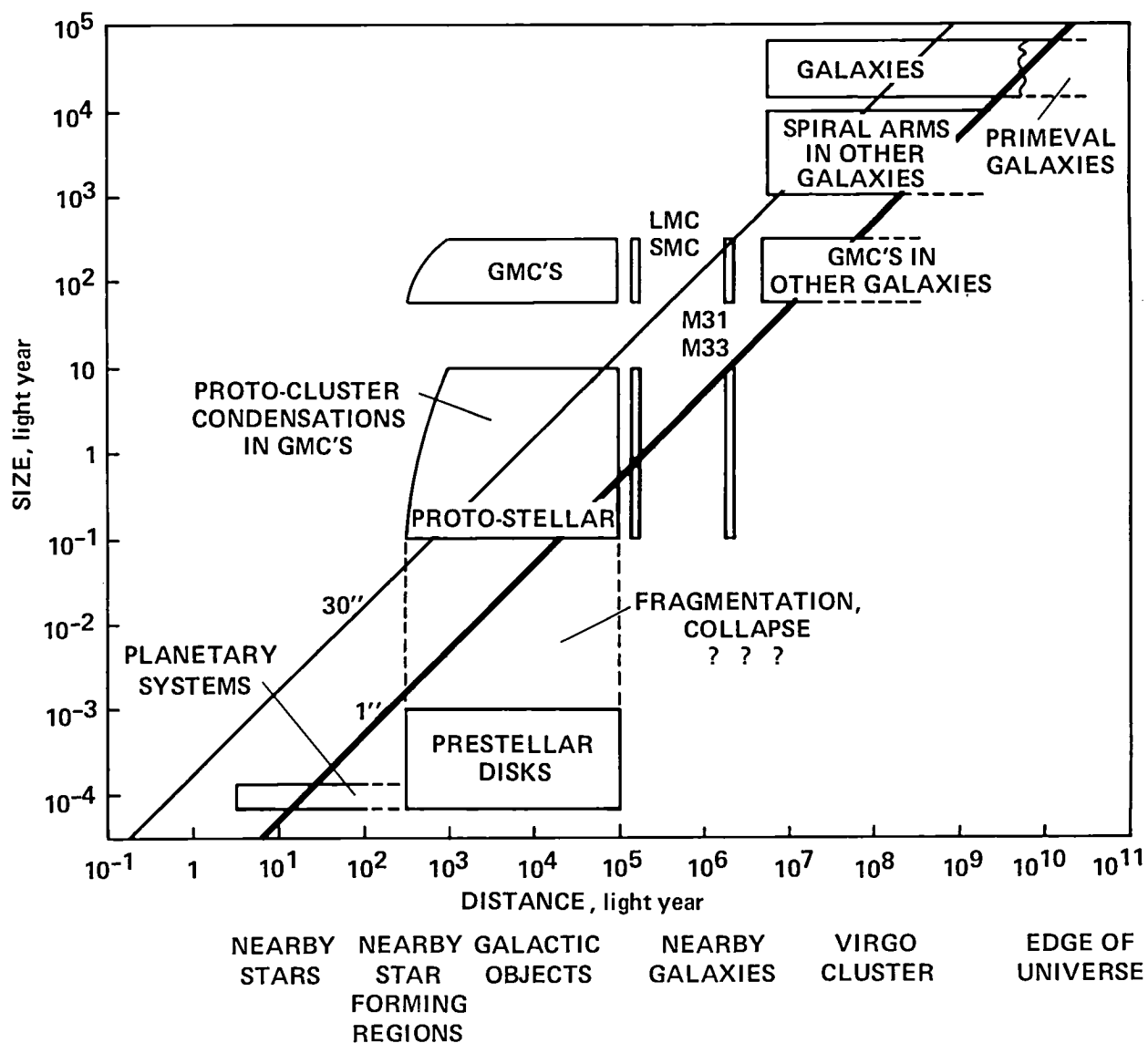


Figure II.1.— The range of sizes of astronomical objects are plotted versus the range of their typical distances. The dark and light diagonal lines plot resolutions of 1 arcsec (typical of LDR at $100\ \mu\text{m}$) and 30 arcsec (typical of SIRTf and other 1 m class telescopes at $100\ \mu\text{m}$). Note that 1 arcsec angular resolution brings into view GMC in other galaxies, the important collapse epoch in star formation between dense interstellar cloud (condensation) and prestellar disk, and possibly planetary systems in nearby stars.

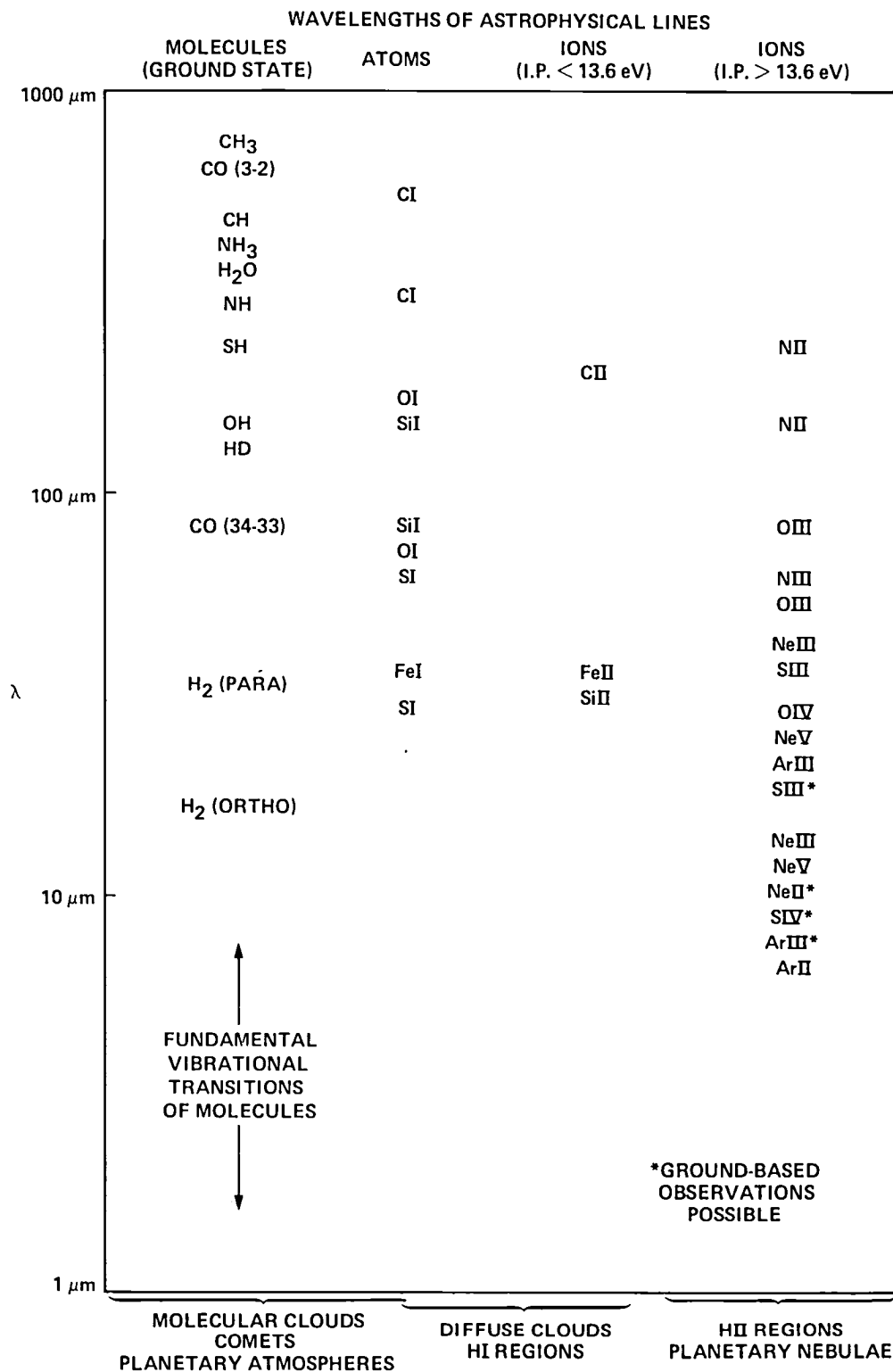


Figure II.2.— The wavelengths and excitation environments of selected astrophysical lines are presented. Note that 30 μm to 1 mm wavelength region includes transitions from the molecular, atomic, and ionic components of astrophysical gas. Ions with ionization potential less than 13.6 eV are plotted separately since these ions may often reside in regions of predominantly atomic hydrogen.

The stellar cycle is completed as stars age and eject their outer layers back into interstellar space, enriching with elements heavier than hydrogen the medium from which subsequent generations of stars and planets will form. The efficiency and large-scale pattern of star formation thus appear to be underlying factors in determining the basic morphology and the basic evolution of galaxies.

Understanding the process of star formation will ultimately require a detailed knowledge of how the tenuous, cold material in the GMC is transformed into objects of stellar density. The same molecular clouds which give birth to stars also hide the process from our view, because the dust prevents any visible radiation from escaping the cloud until after the stellar birth is substantially complete. Furthermore, the earliest stages of star formation are characterized by low temperatures and can therefore be best studied at IR, submillimeter, and radio wavelengths.

Ground-based radio astronomy has revealed the existence of GMC that have sizes up to 300 light-years (ℓ.y.) and the conditions in the clouds as a whole have been assessed by the study of radio frequency transitions of many molecular species. These studies have revealed condensations in the clouds that are likely locations of current and future star formation. The gap between molecular cloud condensation and protostar spans many orders of magnitude in size and density. The condensations have scales of 0.1 to 10 ℓ.y., densities of 10^4 to 10^6 molecules/cm³, and temperatures of 10–30 K, while protostellar disks have sizes of 10^{-4} ℓ.y. densities of 10^{14} molecules/cm³ and temperatures of 300–1000 K.

The relevant temperature range 10–1000 K is one which is uniquely probed by IR and submillimeter observations. The bulk of the dust emission, which generally includes most of the power radiated, falls into this range. Additionally, a large collection of molecular and atomic lines will be excited at these temperatures (see fig. II.2) and provide important data about the composition and motion of the gas.

A telescope having the following capabilities is required for a study of these phenomena:

1. The telescope must be above the obscuring atmosphere because it must operate in the 30 μ m to 1 mm wavelength region, where the bulk of the protostellar radiation is emitted and where the dust is relatively transparent.

2. The telescope must be large to provide spatial resolution capable of probing small regions of star formation and to provide sensitivity for observations at high spectral resolving power.

These requirements point to a large telescope in space, optimized for observations between 30 μ m and 1000 μ m; they point to LDR.

The spatial resolution desired for LDR is in the range of 1 arcsec for wavelengths in the range 2 μ m to 100 μ m and 10 arcsec at 1 mm. Using 1 arcsec as a benchmark resolution, we can see (fig. II.1) that LDR will be able to study the whole range of size scales over which the process of star formation occurs. Taken together, these studies represent a bold new attack on the nature of star formation and evolution extending from broad morphological patterns down to the details of planetary system formation. The galactic orchestration of star formation can be studied in galaxies as distant as 10^8 – 10^9 ℓ.y. Individual GMC and the details of the global pattern of star formation (see fig. II.3) can be studied in galaxies out to 10^7 ℓ.y. The condensations within clouds can be studied in our Milky Way Galaxy and the nearby (distance ~ 300 ℓ.y.) examples can be probed on scales approaching those where protostars are forming (see fig. II.4).

The problem of planetary system formation is closely coupled to that of star formation. Planets around nearby stars might be observed directly by LDR. A search for such planets is crucial to a real understanding of how our solar system formed, but at present, the only clues to this process are to be found within the

solar system. One such clue is the variation of the composition of the solar nebula with distance from the Sun. This variation may be locked into the composition of comets, asteroids, and into the atmospheres of the outer planets, and it can be studied by LDR by spectroscopic observations of these objects.

2. Cosmology from LDR

The importance of IR wavelengths for cosmological studies is a consequence of the expansion of the universe; more distant objects are receding at greater velocities, so that the astrophysical information carried by their intrinsic radiation is shifted toward longer wavelengths. The most striking example of this effect is the cosmic background radiation, the highly redshifted relic of the cosmic fireball in which the universe was born. This radiation permits us to look to an epoch and thus to probe the structure of the early universe, when the universe was only $1/1,500$ of its present size and $1/30,000$ of its present age.

The presently observed temperature of this radiation is 3 K, so that its energy density peaks near a wavelength of 1 mm; a significant fraction of the energy lies at wavelengths < 1 mm. LDR will give unparalleled access to this wavelength range on a finer spatial scale (~ 10 arcsec) than presently attainable. The structure and fluctuations of the cosmic background radiation on this scale are expected to be very small – the radiation is remarkably isotropic on the larger scales which have been studied – but these small-scale fluctuations carry valuable information about galaxy formation in the early universe.

Observations between $600\ \mu\text{m}$ and 3 mm of the effects on the cosmic background radiation of hot gas in clusters of galaxies (Sunyaev-Zeldovich effect) may, in association with observations of X-ray emission from the same gas, provide a new method for determining Hubble's constant. This quantity, which is the ratio of an object's recession velocity to its distance, defines the fundamental distance scale and age for the universe.

LDR is ideally suited to the study of these and other phenomena associated with the cosmic background radiation (see fig. II.5) because it will be free of the atmospheric effects which hamper ground-based studies, and because unimpeded access to the entire submillimeter and millimeter spectral interval will allow searches for the unique spectral signatures produced by each of the processes. High-spatial-resolution studies of the peak and short wavelength portions of the cosmic background radiation will thus be a unique and important capability of LDR.

Other cosmological studies will be carried out if LDR can operate in a "light bucket" mode in the near IR ($\lambda \approx 1\text{--}4\ \mu\text{m}$) with a blur circle of approximately 1 arcsec. At these wavelengths, LDR is well suited for the study of distant galaxies, so highly redshifted ($Z \gtrsim 3$) that the peak of their energy distribution is moved into the $1\ \mu\text{m}$ to $4\ \mu\text{m}$ region.

The angular size and spatial distribution of these very distant galaxies, when compared with observations of nearby galaxies, will help to determine the basic geometry of the universe (i.e., whether the universe is "open" and will continue to expand forever, or whether it is closed and will eventually collapse) and to constrain the evolution of the intrinsic properties of the galaxies. The high sensitivity of LDR in the "light-bucket" mode makes it the only telescope which can push such studies of redshifted galaxies to the confusion limit at which more than one galaxy is seen along each line of sight. No telescope will ever be able to see more distant galaxies than LDR with 1 arcsec angular resolution at $2\text{--}4\ \mu\text{m}$ and mirror temperatures of 200 K or cooler (see fig. II.6).

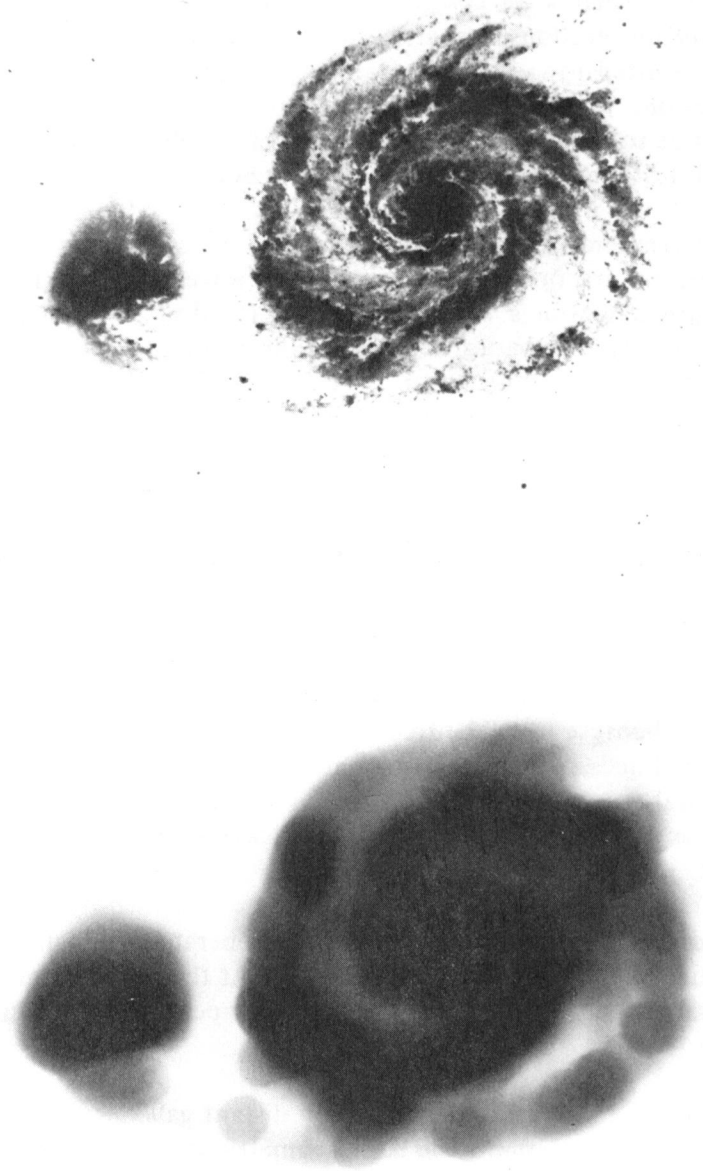


Figure II.3.— The Whirlpool Galaxy (M51) is shown with optical photograph negatives at two angular resolutions. The 1-arcsec-resolution picture (right) is representative of the detail which LDR would uncover in the $100\ \mu\text{m}$ wavelength region. Individual regions of massive star formation (“giant HII regions”) can be discerned as small black dots. The ~ 30 arcsec angular resolution picture at left approximates what 1 m class telescopes such as the KAO and SIRTF can “see” at $100\ \mu\text{m}$.

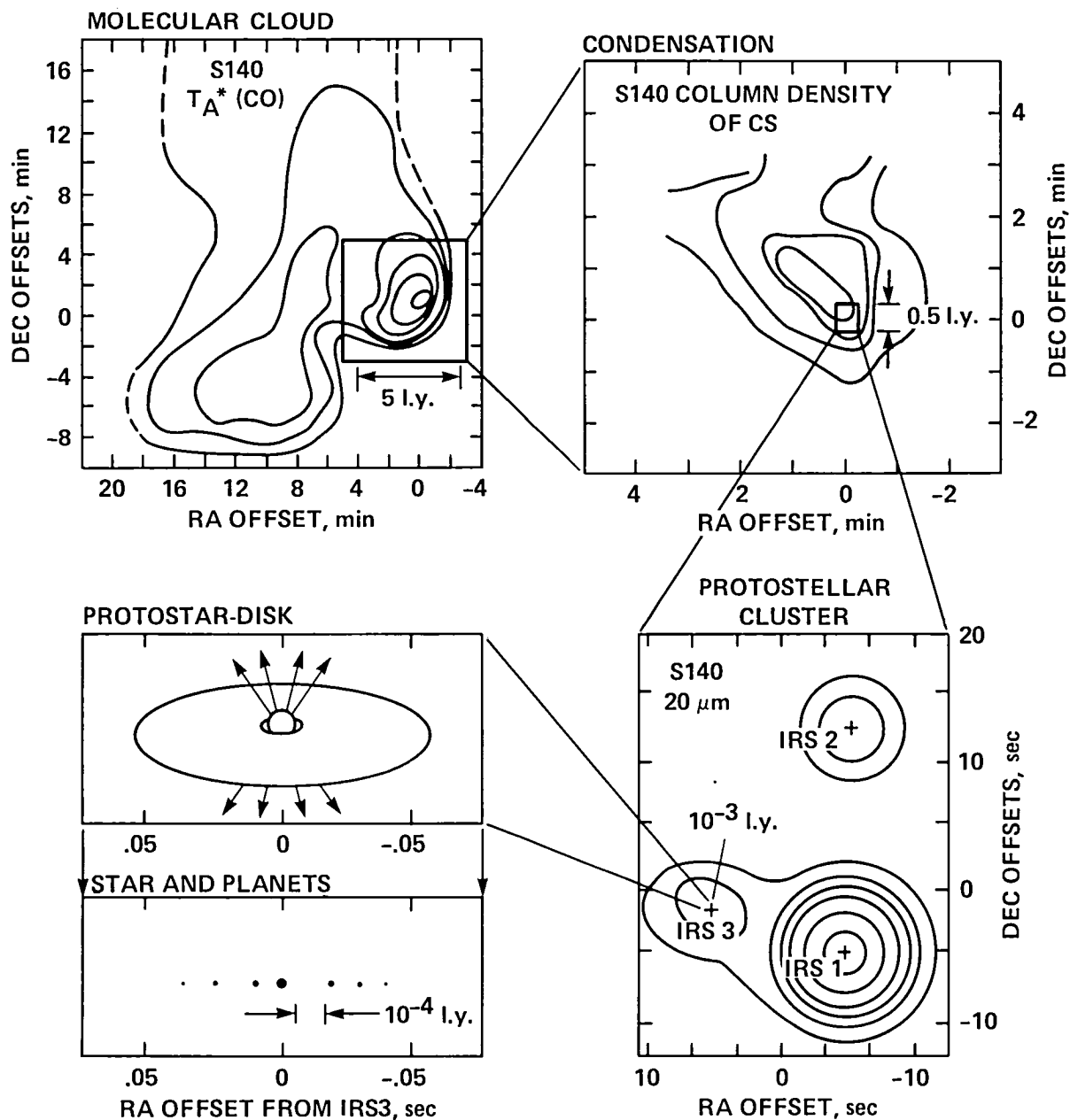


Figure II.4.— Collapse of an interstellar cloud to form a stellar system. At upper left is a map of the molecular cloud associated with S140 (Blair et al., 1978). The map was made in the $J = 1 \rightarrow 0$ transition of CO, an easily excited line which allows a map of the entire molecular cloud. Note that this map, which does not cover the whole cloud, extends for about 20 l.y. The box marks a region of star formation. This region was further studied using four transitions of CS (Snell et al., 1982). The column density of CS, displayed at the upper right, reveals a dense condensation within the molecular cloud (typical density of 10^5 – 10^6 cm^{-3}). Within this dense condensation, a cluster of IR and radio continuum sources has been found (Beichman et al., 1979), as shown at lower right. This map covers about 0.3 l.y. with a resolution approaching 0.015 l.y. If we could examine the region on still smaller scales (~ 0.001 l.y.), we might hope to study the process of formation of individual stars (shown schematically at the lower left). These stars are known to produce copious outflows of matter, often in a bipolar pattern, which may be produced by a protostellar disk. This system may in turn evolve into a star and planetary system like our own.

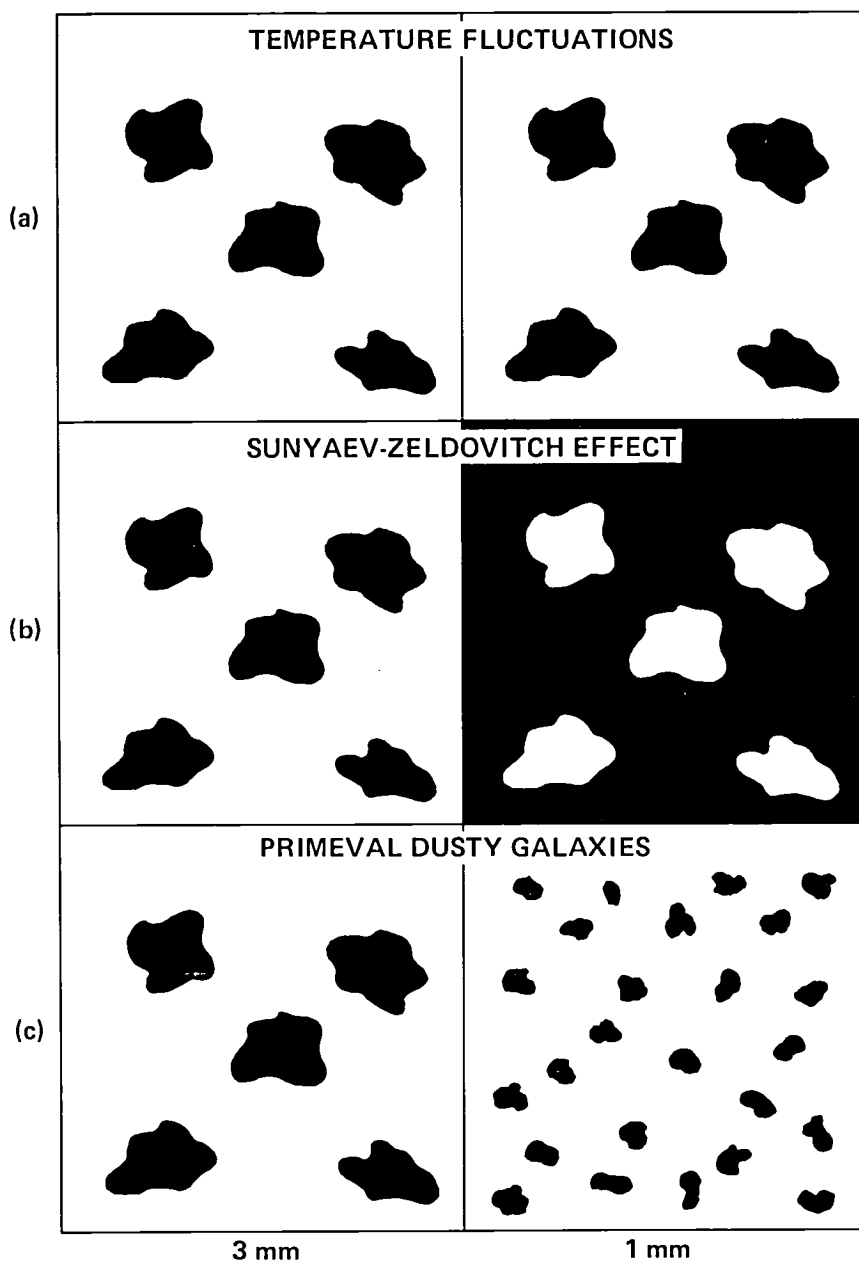


Figure II.5.— Photographs of three possible cosmological processes at two wavelengths (3 mm and 1 mm). The dark areas indicate regions of smaller intensity. These three processes may look similar at 3 mm, but will be differentiated by 1 mm observations only accessible to LDR. Temperature fluctuations in the early universe will produce similar pictures at 3 mm and 1 mm; the Sunyaev-Zeldovich Effect (see discussion in III C) produces a negative image at 1 mm compared to 3 mm; dusty primeval galaxies may not produce correlated pictures at 1 mm and 3 mm.

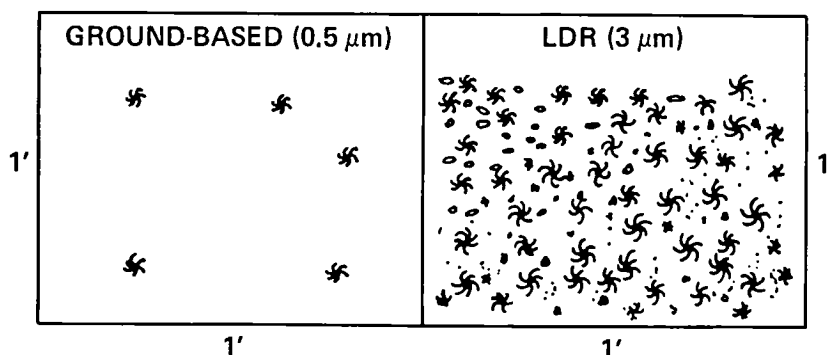


Figure II.6.— Light bucket viewing of distant galaxies with LDR. A schematic drawing which illustrates dramatically the galaxies seen in a 1' by 1' field with LDR compared to typical ground-based optical viewing.

3. Major Telescope Requirements Derived from Science Rationale

We conclude by summarizing the major conclusions of the Asilomar science workshop concerning the telescope requirements derived from scientific rationale. It was agreed that, since much of the astronomy anticipated is spectroscopic, the telescope need not be at temperatures $<150\text{--}200\text{ K}$. This can be achieved by passive cooling and a sun shield. The angular resolution required to provide a major step in our understanding of star formation is about 1 arcsec. For the characteristic wavelength of $100\text{ }\mu\text{m}$ this implies a telescope of approximately 20 m diam.

The reflecting surface should be sufficiently accurate to provide diffraction limited performance to about 30 to $50\text{ }\mu\text{m}$. As a secondary goal, it would be desirable to have the capability for making observations in a light bucket mode in the $1\text{--}4\text{ }\mu\text{m}$ range, with a blur circle of about 1–2 arcsec. Such capability would give LDR unprecedented power in detecting distant galaxies, determining the overall structure of the universe, and predicting its ultimate fate.

B. GENERAL DESCRIPTION OF THE LDR

A goal of the Asilomar conference was to begin to define the physical parameters of LDR which would be required to achieve the currently anticipated astronomical objectives. As currently conceived, LDR is an approximately 20-m diam reflecting telescope deployed in space with a single shuttle launch. Presently, we envision a free-flying observatory. However, it may be attached to a proposed Space Platform, and it may eventually involve several shuttle launches and include multiple components. It will be operated as a major national observatory with a lifetime of 10 or more years. Revisits may occur more frequently to replenish cryogen and change instruments.

The physical configuration of LDR is not yet certain, and the project poses many intriguing technical challenges. Before considering the detailed astronomical objectives, there are some obvious factors to take into account. The weight and volume constraints of the shuttle, the demands of the space environment, and the projected status of technology available for LDR limit the range of options available. Preliminary technical studies have defined the following general characteristics which any design for LDR must have:

1. Because of the limited size of the shuttle bay, which is 4 m wide, a larger LDR cannot be carried into orbit as a unit. Instead, the reflector surface may have to be built from smaller panels or mirror

segments, less than 4 m diam. These panels and their associated backup structure must be deployed or assembled in space to form the finished telescope. One exception to this might be a 4 by 18 m rectangular mirror.

2. The panels themselves must be of low areal density (mass/m² of reflector) because of the limited carrying capability of the shuttle. For a 20 m diam LDR, the maximum allowable areal density of the reflecting surface is about 50 kg/m². This is considerably lower than the areal density of conventional optical telescopes (for comparison, the ST mirror has an areal density of approximately 180 kg/m²), although glass panels of areal density \ll 100 kg/m² have been fabricated. By contrast, precision high-frequency radio telescopes now operating at submillimeter wavelengths longward of approximately 300 μ m have areal densities as low as 20 kg/m². A lightweight mirror panel capable of meeting the LDR requirement of 30 μ m diffraction limit has not yet been built and finding a suitable panel material is a major technological challenge to the project.

3. Both the expected imprecision of the deployment process and the response of the segmented surface to the varying thermal and mechanical disturbances during its orbit require that the relative positions of the panels be controlled; some form of "active optics" will be required to maintain acceptable image quality. This requires a means of sensing the positions of the panels (or the quality of the image) and a means of moving the panels to achieve the desired figure. It is not anticipated, however, that the figure of each individual panel will have to be controlled.

4. LDR should be thermally stable to minimize corrections to the surface figure and to prevent degraded performance in the sensitive IR detectors. For these reasons, LDR must be provided with a sunshade to shield the surface from direct sunlight; limits on how closely the line of sight can approach the Sun will also be necessary.

In summary, LDR is conceived as a telescope with a segmented, actively controlled primary mirror which is fabricated of extremely lightweight materials. A sunshade will be required for thermal protection of the system. The telescope will probably be carried into space in a single shuttle launch and be deployed or assembled in space before being placed in orbit. Atmospheric drag on the large surface area may require an orbital altitude of \sim 700 km instead of the normal \sim 300 km operating limit of the Shuttle, so that an additional propulsion unit may be part of the package.

These preliminary considerations were combined with the astronomical and technical considerations at the workshop to produce a set of performance requirements and baseline system parameters. These appear in table II.1 and an artist's conception of what such a telescope might look like is shown in figure I.1.

The scientific instruments to be used for observations on LDR should be carried into orbit by the same Shuttle flight which carries the telescope. The present status of the rapidly changing technology of IR and submillimeter instruments is reviewed in the companion volume. Here, we describe in general terms the types of instruments that will be required to carry out the scientific program described in section III. Early versions of some of those instruments are currently in use on airborne, balloon-borne, and ground-based telescopes. More detailed discussion appears in section IV.

Because the main scientific payoff from LDR will result from observations at high spectral and spatial resolving power, emphasis will be placed on instruments to achieve good resolution. For the highest spectral resolution, coherent detection with heterodyne techniques similar to those of radio astronomy can be used at submillimeter wavelengths. Spectral resolving power ($R = \nu/\delta\nu = \lambda/\delta\lambda$, where ν is the frequency, $\delta\nu$ or $\delta\lambda$ is

TABLE II.1.— LDR SYSTEM PARAMETERS AND PERFORMANCE REQUIREMENTS

Parameters	Requirements
Diameter	20 m primary, 1 m secondary
Field of view	≥ 3 arcmin
F/Ratio	System F/10, primary F/0.5
Shortest wavelength of diffraction-limited performance	30–50 μm (aperture efficiency $> 30\%$ at 30 μm)
Light bucket blur circle ^a	2.0 arcsec (at 1–4 μm)
Optics temperature	Primary ≤ 200 K (± 1 K uniformity), secondary ≤ 125 K (± 1 K uniformity)
Emissivity (system)	0.05
Absolute pointing	0.05 arcsec
Jitter	0.02 arcsec — within 1 min after slew
Slew	$\geq 50^\circ/\text{min}$
Scan	$1^\circ \times 1^\circ$ — linear scan at $1^\circ/\text{min}$
Track	$0.2^\circ/\text{hr}$ (for comets $\geq 25^\circ$ from Sun)
Orbit requirements ^b	750 km altitude
Chopping	Yes, 2 Hz, 1 arcmin (reactionless)
Sidelobes	Low near sidelobes
Other	Limited cross polarization
Thermal shade L/D	1
Sky exclusion	$\geq 90^\circ$ Sun from Sun, $\geq 45^\circ$ from Earth
Cryo system	Various temperatures in the range 0.1 K to 50 K, 1.5 kW total power required
Lifetime	> 10 yr, approximately 3 yr revisit
Deployment mode	Person(s) assisted (if necessary)
Mass	27,000 kg total (one shuttle)
Weight of instruments	3000 kg (including cryogen)

^aThe tolerances (e.g., rms surface accuracy) needed to achieve a value of 2 arcsec for the light bucket mode are more severe than the tolerances associated with a diffraction limit of 50 μm . This requirement will be studied further.

^bPolar orbit desirable but may require multiple shuttle flights. Particle radiation may cause consideration of a lower orbit.

the resolution, and λ is the wavelength) in excess of 10^6 can be achieved with these techniques, at least to wavelengths as short as 100–200 μm . For shorter wavelengths and/or lower spectral resolving power (perhaps in the range $R = 100$ to $R = 10^4$ – 10^5), spectrometers of various types — grating instruments and Fabry-Perot and Michelson interferometers — will probably be used. The detectors to be used with these spectrometers would include both IR-sensitive, photoconductive devices and bolometers, the latter being used at the longer wavelengths (≥ 200 μm). Both single- and multi-element (array) detectors will be used with the spectrometers.

Broadband photometric and mapping observations can be carried out with a variety of instruments based on detectors similar to those described above. We can anticipate, however, that in the LDR era monolithic IR arrays will be in wide use. An array can be incorporated with a suitable optical system into an IR camera which will provide images at IR wavelengths and utilize the spatial resolving power of LDR.

A range of filters permitting observations of narrow spectral features will be incorporated into such a camera; additionally, the camera could be used in tandem with a spectrometer for true spectral imaging. Polarizers could be added to the system so that polarization measurements could be made. For certain types

of specialized measurements (e.g., high-time resolution studies) a single detector optimized for a particular purpose may be preferable to an array. We can anticipate that most instruments will require some form of cooling to temperatures from 0.1–50 K for satisfactory operation, so that cryogenic systems will accompany the telescope and instruments into space.

C. COMPARISON OF LDR WITH OTHER TELESCOPES

1. Current and Future Infrared and Submillimeter Telescopes

A 20-m diam LDR would provide approximately 20 times better spatial resolution and 400 times more collecting area than the 1-m class airborne and balloon-borne telescopes now in use at wavelengths between 30 and 600 μm . The increased aperture leads to a dramatic jump in scientific capability and makes possible the exciting and important investigations described herein. At some wavelengths between 300 μm and 1 mm it is sometimes possible, though difficult, to observe from mountaintop sites; large ($\gtrsim 10$ m) ground-based telescopes for this purpose will certainly come into use before LDR is launched.

Like the airborne and balloon-borne telescopes, these ground-based telescopes will be important scientific and technical precursors of LDR; however, the atmospheric windows in the 300 μm to 1 mm range are narrow and variable. For most purposes, the total freedom from atmospheric effects should make LDR much more powerful than a comparably sized ground-based telescope, which, in any case, could not operate in the LDR primary range of 30–300 μm . Similarly, if LDR can be used in the light-bucket mode at $\lambda \lesssim 4 \mu\text{m}$, LDR will be much more sensitive in the near-IR than even the 10–20-m diam New Technology Telescopes projected for the next generation. This is a result of lower LDR temperature and the absence of atmospheric attenuation and emission; supporting calculations can be found in appendix A.

LDR will also complement other space telescopes planned for IR observations over the coming decade. Comparison of LDR with the Cosmic Background Experiment (COBE), the Infrared Astronomical Satellite (IRAS), and the Shuttle Infrared Facility (SIRTF) – each cryogenically cooled and, therefore, very sensitive – is particularly instructive. COBE is designed explicitly to study the diffuse cosmic background radiation. Its three instruments span the wavelength range from 1 μm to 1 cm. The highest angular resolution achievable from COBE will be 1° ; its finds will thus be complemented by the higher angular resolution provided by LDR. These fine-scale measurements are crucial for investigating small-scale signals from the galaxy-formation epoch.

IRAS (size ~ 0.6 m) will survey the sky at IR wavelengths to very low flux levels and catalog tens of thousands of previously unknown sources, many of which will be seen primarily with a spatial resolution of approximately 100 arcsec at 60 and 120 μm , wavelengths where LDR will be very powerful. IRAS has no spectroscopic capabilities for wavelengths longer than about 30 μm . Because of its much larger aperture and spectroscopic capabilities, LDR will be sensitive enough to study many IRAS sources in great detail and will give us our first information on the sizes and structures of the sources on scales $\lesssim 30$ arcsec.

SIRTF (size approximately 1 m) will be an observatory-class facility with interchangeable focal-plane instruments. It is designed to operate from 1.8 to 700 μm , and its very cold (10 K) optics will make it 100 to 1000 times more sensitive than presently existing IR instrumentation from 5 to 200 μm . SIRTF will therefore open many new fields for study and exploration in the infrared. LDR is designed to be especially effective in the submillimeter ($\lambda \gtrsim 200 \mu\text{m}$), where telescope cooling is not so important and possibly also at 1–4 μm , shortward of its own emission peak. The spatial resolution of LDR will be far greater than that of SIRTF. LDR will also be much more sensitive for many spectroscopic observations; the temperature of the optics matters little at high spectral-resolving power.

The relative capability of LDR can be seen in figure II.7, where spectral resolving power is plotted versus frequency. For $R \gtrsim 10$ (depending on the noise produced by the SIRTf detectors) the large collecting area of LDR will make it more sensitive to small sources than SIRTf at all frequencies. For extended sources, SIRTf will be superior at larger R , as can be seen in the figure. LDR will out-perform larger millimeter wave telescopes on the ground (e.g., the telescope at the Institut de Radio Astronomie Millimetrique – IRAM) at wave lengths below about 1 mm and will be the telescope of choice for spectroscopy down to wavelengths as short as it can be made to work. At that point, the smaller ST and large ground-based telescopes will be preferred. The calculations supporting these statements can be found in appendix A.

2. Facilities for Use at Other Wavelengths

LDR, as the first major facility for far IR and submillimeter wavelengths, is comparable in magnitude and scientific importance to current and planned major facilities being developed for use in other spectral bands. Scientifically, LDR complements ST, AXAF, and large ground-based radio and optical telescopes.

LDR will provide images of galaxies in the far IR with angular resolution comparable to that obtained in photographs from the ground. Similarly, LDR will explore regions of star formation mapped with comparable angular resolution in lines of CO and the NH_3 by advanced millimeter-wave interferometers and by the Very Large Array radio telescope (VLA). LDR studies these regions at the wavelengths where they emit most of their energy and will therefore have many magnitudes more sensitivity than the millimeter instruments – enough to detect advanced stages of star formation and the formation of planetary systems.

As a mature observatory, LDR will not just complement telescopes that operate at neighboring wavelengths. For instance, LDR studies of the Sunyaev-Zeldovich effect in clusters of galaxies will be combined with X-ray observations from AXAF to determine Hubble's constant.

Facilities like LDR, ST, AXAF, and the VLA bring immense increases in capability to their respective disciplines. The recent history of the astrophysical exploration shows that such leaps in instrumental capability lead to the solution of pressing astrophysical problems and to the discovery of entirely new phenomena.

LDR will bring major advances in performance for high spatial and spectral resolution work across almost three decades of wavelength from 2 to 1000 μm . These advanced facilities together will attack astrophysical problems across the entire frontier. LDR, with its unique capabilities for studying cosmology and star formation, will play a crucial role in these investigations and become one of our major resources for astronomical research for decades.

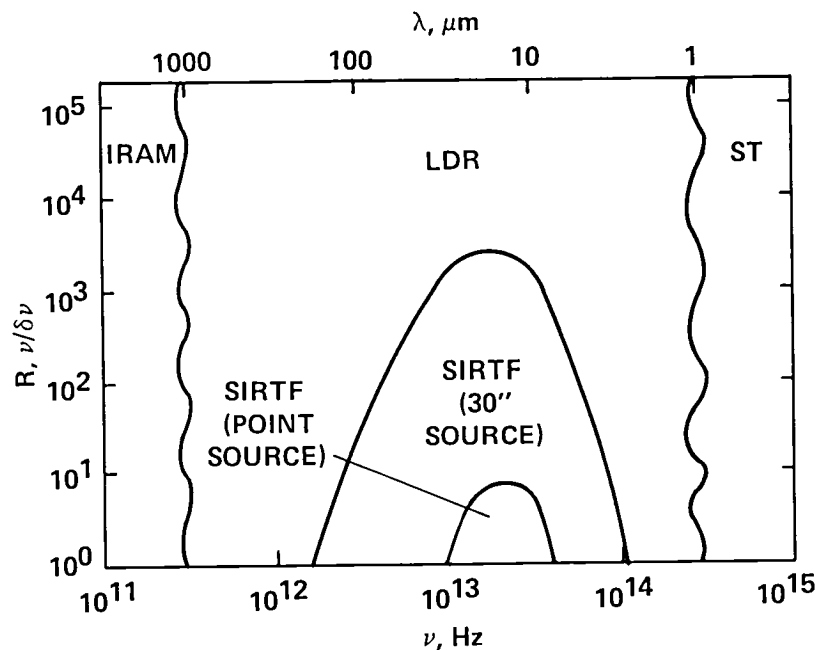


Figure II.7.— Comparison of LDR with other telescopes. The areas in which various telescopes will excel are indicated in the plane of resolving power, $R \equiv \nu/\delta\nu$, and frequency (wavelength is indicated at the top). As shown in appendix A, LDR will be more sensitive to unresolved sources than SIRTf, except for photometric observations ($R \lesssim 3$) in the mid-IR ($\lambda \sim 6\text{--}30\ \mu\text{m}$), the regime for which SIRTf was designed. LDR will excel over ST for all wavelengths for the assumed 2 arcsec blur circle. At that point where this blur circle degrades, ST will have to take over. At wavelengths longer than $1000\ \mu\text{m}$, large, ground-based millimeter wave telescopes such as the 30-m IRAM telescope will excel, although poor atmospheric transparency makes the exact boundary here uncertain. The assumptions about LDR used to make this figure are as follows: 20 m diam; shortest wavelength at which diffraction limited, $\lambda_c = 30\ \mu\text{m}$; the beam size is diffraction-limited for $\lambda < \lambda_c$ and 2 arcsec for $\lambda > \lambda_c$; the telescope temperature is 200 K and emissivity is 0.05. Detector (NEP) of $10^{-17}\ \text{W/Hz}^{1/2}$ were assumed; better detector NEP would improve SIRTf relative to LDR and vice versa. SIRTf will improve relative to LDR for extended sources as shown in the figure for the case of a 30 arcsec diam source.

III. SCIENTIFIC RATIONALE

A. GENERAL RATIONALE

We now consider in greater detail the scientific objectives for a large deployable reflector. The fundamental concept of LDR is a large, ambient-temperature space telescope which, by virtue of its size, will bring a large increase in spatial resolving power and spectroscopic sensitivity over existing and planned submillimeter and infrared telescopes. This concept is driven by our historical experience in the radio and optical regions, where imaging and spectroscopic capabilities brought dramatic advances in our understanding of the universe. To obtain an order of magnitude increase in spatial resolving power, LDR is conceived as being 20 m in diam, and diffraction-limited for wavelengths longer than 30 μm . LDR will therefore obtain the highest possible spatial resolution in the 30–300 μm region, where large, ground-based telescopes cannot operate.

Given these general capabilities, we can identify some astrophysical areas in which the LDR will make major discoveries and contributions to our understanding of the universe. In turn, the required observations may affect the major telescope parameters (e.g., size and operating wavelength) as well as many other system parameters (e.g., field of view, instrument complement, and chopping requirements).

A 20 m diam telescope (1 arcsec resolution at 100 μm) baseline was adopted as a telescope which appeared technically feasible for the 1990s. In the scientific rationale which follows, we discuss many likely observations which a 20-m LDR will perform and the important requirements these observations place on the telescope.

B. ORIGIN AND EVOLUTION OF STARS AND PLANETS

1. Star Formation on a Galactic Scale

In the last few years IR studies have taught us that most spiral galaxies, and a few elliptical galaxies, emit the bulk of their energy in the 30–1000 μm IR range. In the majority of cases, the emission arises from the interstellar gas and dust associated with the disks and spiral arms of galaxies. This emitted material is heated partly by the vast numbers of stars in the galaxy, but most particularly, by groups of bright, newly formed stars which strongly illuminate and heat the matter in the vicinity of the stellar birth-sites. The stellar birthplaces are obscured from optical view for millions of years and therefore can only be seen in the infrared and radio.

In a smaller number of galaxies the central regions (“nuclei”) are anomalously bright and vastly outshine the disks. Extreme examples of these objects are quasars and blazars (objects resembling BL Lacertae) which can emit up to 10^{13} solar luminosities (L_{\odot}) of energy from volumes no bigger than 1 k.y.; similar, though less powerful, activity is found in many other galaxies.

In some of these objects the activity appears to be linked with bursts of star-formation in the central regions; but in the very luminous quasars and blazars, it seems likely that processes other than star formation are responsible for the high luminosity. In any case, it is important to image the central region and resolve star-forming regions from each other and from the powerful and mysterious “engines” that appear to drive some active nuclei.

The LDR will be unrivaled for studying the disks and the nuclei of galaxies; its main advantages are that (1) LDR operates at wavelengths where these regions are the most luminous and where dust is practically transparent, and (2) LDR possesses sufficient spatial resolution to isolate important parts of galaxies.

The three most important programs in galactic studies which LDR will allow us to undertake are described in more detail in succeeding sections: in section (a), we discuss how LDR can be used to study global patterns of star formation in galaxies to determine where, and under what conditions, stars form; in section (b), we consider the potential of LDR for the study of the nature and cause of intense nuclear activity in galaxies; in section (c), we show how LDR will allow a study of the impact of stellar formation and evolution on galactic properties over the lifetime of the galaxy.

(a) *Global patterns of star formation in galaxies*— Fundamental to our understanding of galactic structure and evolution are observations of the luminous young stars and interstellar matter from which they condense. For the first time, LDR will enable optical quality imaging (1 arcsec resolution, see fig. III.1) in the far IR of both the continuum emission from the dust component of the interstellar medium and the line emission from the gas component. The line emission characterizes three important phases of the interstellar gas: the cold molecular phase traced by the fine structure lines of atomic carbon, rotational transitions of the hydrides such as H_2O , and heavier molecules such as CO; the warm atomic phase traced by fine structure lines of C^+ and O, its dominant coolants; and the hot ionic phase traced by ionic fine-structure lines such as those of O^{++} and N^{++} . Submillimeter and far-IR emissions from all three of these phases have been shown to be associated in our own galaxy with regions of star formation.

One important observational study of LDR involves the detailed mapping of nearby galaxies within a few million light years of the Earth. Here, the LDR, with its spatial resolution of ~ 30 l.y., will test two competing theories of massive star formation associated with the spiral patterns. If massive star formation is triggered by spiral density waves, we would expect separation around the spiral arm among the atomic, molecular, and ionic gas phases. On the other hand, if massive stellar births are triggered more randomly, these separations would have little global symmetry. It is interesting that in the nearest galaxies, LDR will be able to resolve individual molecular clouds, thus addressing the issue of whether cloud properties (e.g., temperature or mass) are different at different radii in the galaxy or in spiral arms versus interarm locations (see fig. III.1).

A specific example of the unique ability of LDR to detect all phases of the interstellar medium with good angular resolution, without dust obscuration, can be given for the galaxy NGC 4736 (see fig. III.2) which lies at an intermediate distance of 14×10^6 l.y., from Earth. On the optical photo one sees the spiral pattern delineated by HII regions and dust clouds winding to within approximately 20 arcsec of the nucleus. The present data at $\lambda = 160 \mu\text{m}$, obtained on the KAO with 30 arcsec resolution, clearly show emission peaks correlated generally with the ring of HII regions. Determining the actual relationship between the atomic gas, the molecular clouds, and the areas of massive star formation requires much better resolution. For example, we would like to determine the variation in the relative properties of the different phases of hydrogen when a wave of density enhancement, which appears as a spiral arm, passes across a part of the galaxy.

(b) *Galactic nuclei*— The nuclei of some galaxies are known to contain compact nonthermal sources with scale sizes < 150 l.y. Some of these sources, such as quasars, are very luminous; they may emit more power than all the rest of the galaxy. Much of the power of these sources is emitted in the infrared. Even when the far-IR is not the dominant spectral region, it contains information which may be crucial to understanding the sources (e.g., the presence of spectral “breaks” and features as signatures of the specific

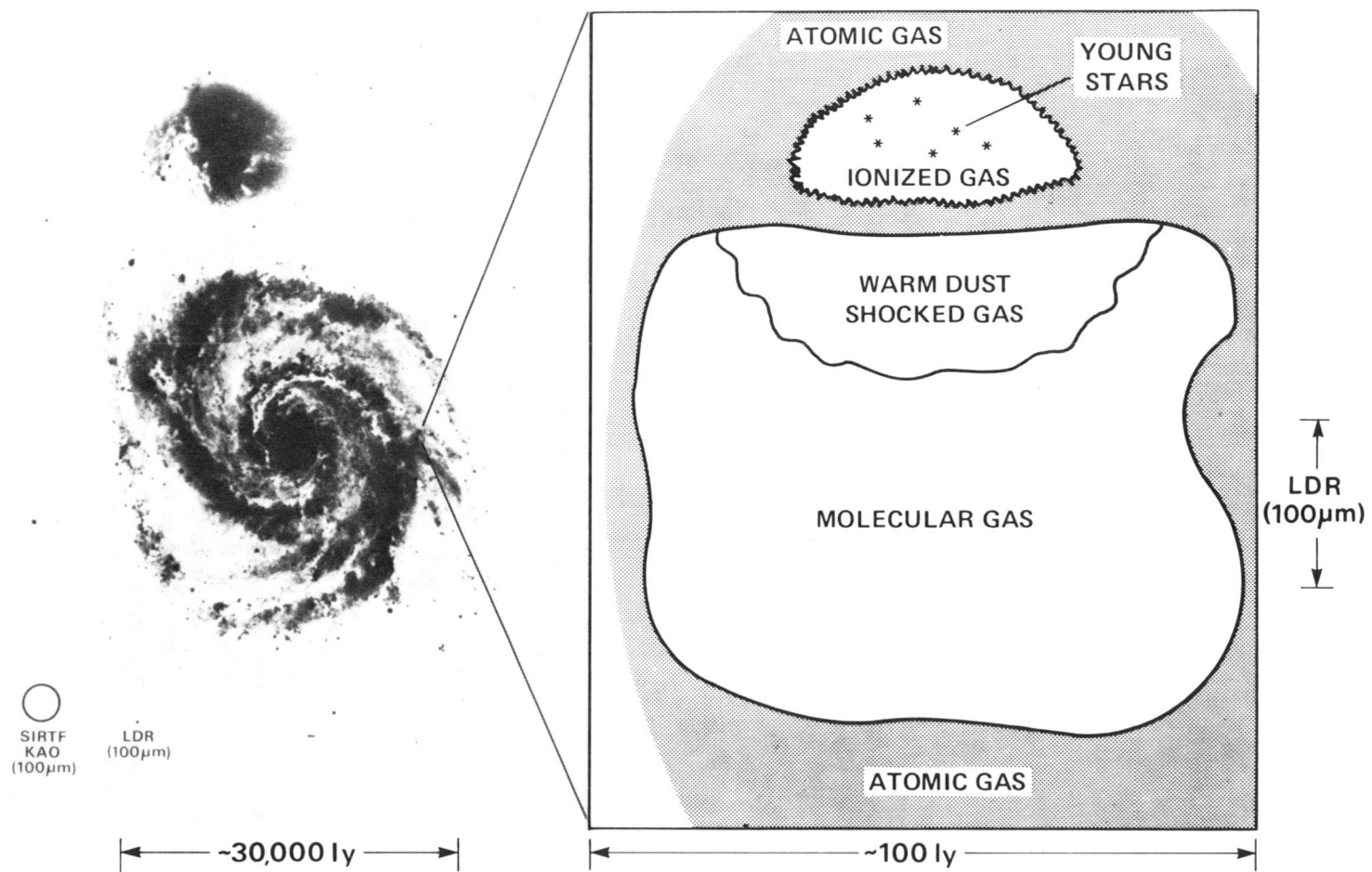


Figure III.1.— LDR resolves gas components in external galaxies. The optical photograph of the Whirlpool Galaxy (M51) is shown at left with the beam sizes of the KAO, SIRTf, and LDR superimposed. LDR will resolve the overall distribution of atomic, ionic, and molecular components of the gas across spiral arms. The relative positions of those components will help determine global properties of star formation. In nearer galaxies, individual giant molecular clouds will be resolved. A possible spatial scenario for such a cloud is shown in the diagram above.

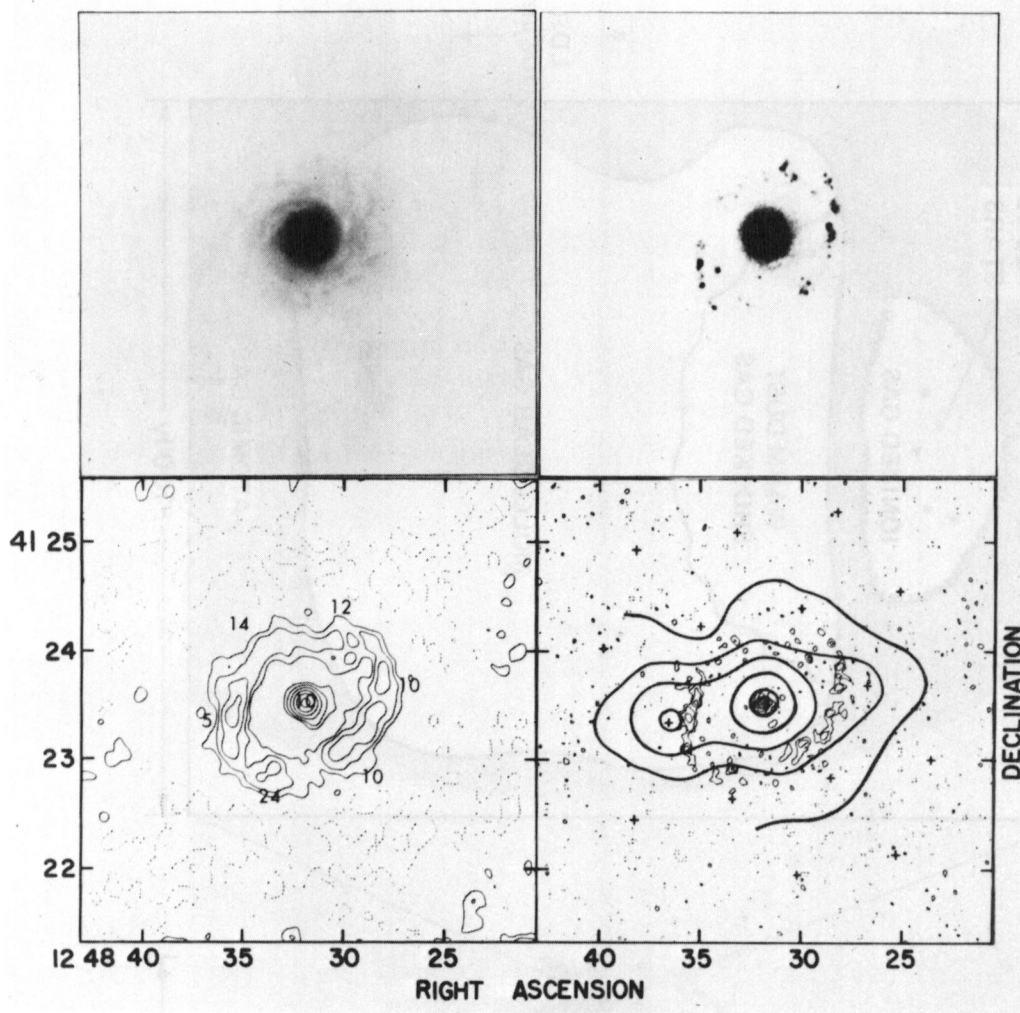


Figure III.2.— Optical IR and radio maps of NGC 4736 (M94). Lower right: 160 μ m map of NGC 4736 superposed on an untapered, 6-cm VLA continuum map. The half-power beam was 49-arcsec diam. Crosses mark positions measured in the far IR. Note that undersampling may slightly distort the map contours. Contour levels are linear in steps of 5.6 Jy, and the peak intensity is 30 Jy into a 49-arcsec beam. The statistical significance of the lowest contour is approximately 2σ . Lower left: Ratio of 115 to 160- μ m flux density (normalized to 10 at the nucleus) superposed on a smoothed 6-cm continuum map (16,000 wavelength Gaussian taper). Upper left: Visual continuum (from D. Hamilton, Yerkes Observatory). Upper right: H α (from B. T. Lynds, 1974). The figure is taken from Harper (1982).

emission mechanisms). The magnitude and variability of far-IR emission and polarization all contain clues to the sources structure, dynamics, and the magnetic-field strength and orientation.

Many galaxies also contain luminous, extended regions of star formation with the central few thousand light years of their disks. These regions also emit predominantly in the infrared, and the luminosities of these regions may equal or exceed those of the compact nuclear sources. Separating the contributions of compact nuclear sources from those of extended regions of star formation requires good angular resolution; resolution of 1 arcsec would allow one to discriminate 300 $\ell.y.$ at $6 \times 10^7 \ell.y.$ and 1500 $\ell.y.$ at $3 \times 10^8 \ell.y.$ With such a resolution, one could begin to separate “compact” and “extended” components of the nearest “active” galaxies and to determine the causal relationships between the compact, nonthermal activity and the extended starforming regions. In figure III.3, one can see the detail which 1 arcsec resolution would bring to the study of the galaxy NGC 1068, which shows evidence for both star formation and compact, central, nonthermal activity.

LDR will extend the study of nuclear activity to galaxies with relatively quiescent nuclei. In the recent past, some of these galaxies may have experienced intense bursts of nuclear activity whose effects might still linger in the physical properties (motion, degree of ionization) of the surrounding medium. The far-IR lines detectable by LDR will be an important diagnostic of these properties. The LDR will help determine how frequently such phenomena occur, how long they last, and in which type of galaxies they are most prevalent. The LDR will also help measure the distribution in the luminosities of the active phases of nuclear activity.

Of particular interest is the center of our Milky Way Galaxy, which contains a very compact nonthermal radio source, possibly a massive black hole, within a cluster of arcsec-scale (0.2 $\ell.y.$) ionized clouds distributed over the central arcmin (10 $\ell.y.$) of the stellar “core” region. The galactic center is completely obscured at optical wavelengths. Figure III.4 shows ground-based radio and near-IR maps which delineate the arcsec structure of the ionized gas.

Continuum and spectral line observations at 1 arcsec resolution in the far-IR will help distinguish star-forming regions from regions ionized by the nonthermal source, will probe evidence of recent energetic bursts of nuclear activity, and will help differentiate star-forming regions near the galactic center from those farther out. Resolution of an arcsec would allow resolution of Orion-type clusters at the distance of the galactic center for continuum and line observations.

The small spatial scale of the activity in our own galactic nucleus and the small sizes of active nuclei derived from light travel times suggest that ultimately much higher angular resolution (0.01 arcsec) will eventually be required to study the powerful engines of nuclear activity. For this and other applications detailed below, LDR might eventually be considered as a single element in a submillimeter/far-IR interferometer.

(c) *The history of star formation in galaxies*— Our understanding of stellar evolution will be vastly aided by knowledge of the history of star formation. The pattern of star formation over time can be inferred from spectroscopic maps of nearby galaxies or from spectra of galaxies at large red shift. The first method looks at the history of star formation and nuclear synthesis rates required to produce the observed spatial distribution of elements more massive than helium. The second method employs two approaches: looking at starlight to find the ratio of young blue stars to old red stars and measuring the total heavy element abundances in the interstellar gas of distant (younger) galaxies.

Elements heavier than hydrogen are formed in nuclear reactions in stellar interiors and are sometimes returned to the interstellar medium upon the death of the star. Measuring elemental abundances in a galaxy therefore provides a clue to the history of star-formation rates in the galaxy. In particular, variations in the

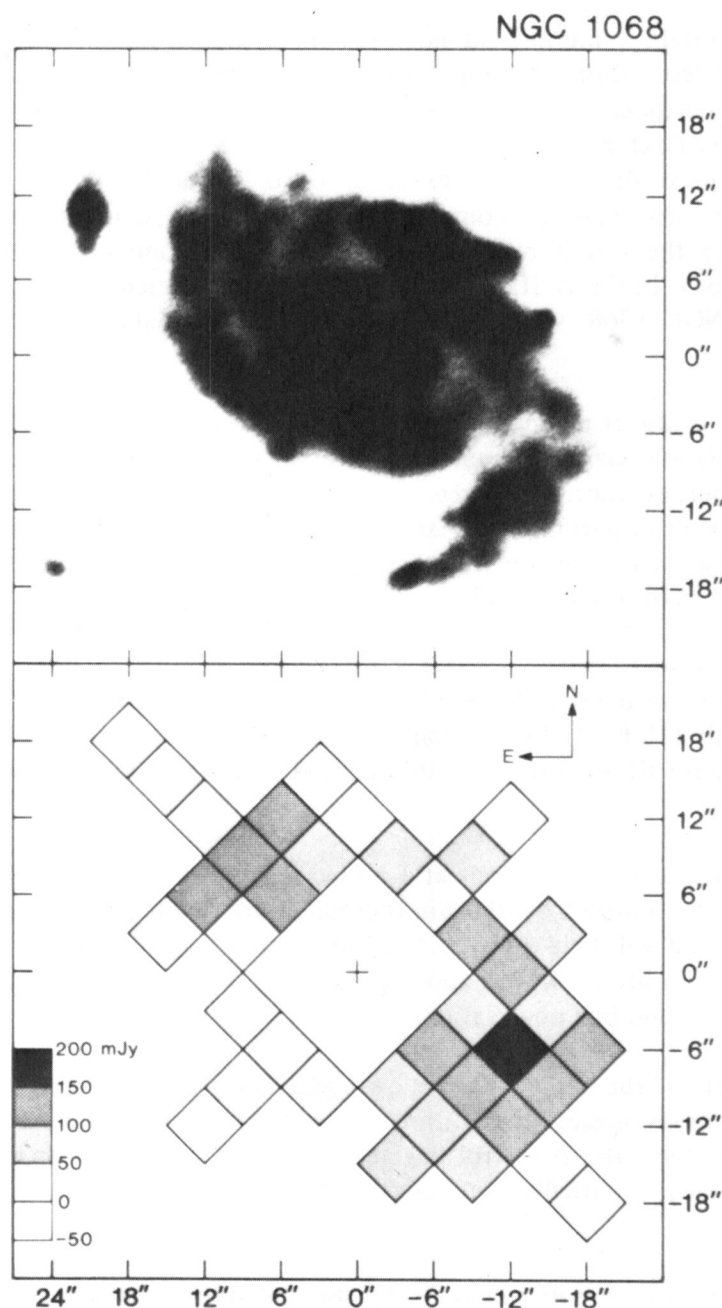


Figure III.3.— LDR resolves the active nucleus from the star-forming regions in NGC 1068. The right optical photograph (approximately 2 arcsec resolution) shows the central 30 arcsec of the active Seyfert galaxy NGC 1068. This galaxy is thought to have a nonthermal active nucleus with a surrounding region of star formation (spiral patterns 6 arcsec to 15 arcsec from center). The left map shows the 10 μ m continuum observed with approximately 5-arcsec resolution. The central region is very intense and not included in the map. The 10 μ m and optical photographs appear to correlate and point to star-forming regions. Note that 30-arcsec resolution of KAO or SIRTIF fails to resolve nucleus from star-forming region. LDR will map and measure the motions of all phases of the gaseous medium in the star-forming region and the region surrounding the nucleus. Shocked gas may also be detected judging from 2- μ m H_2 emission observed in these regions. This figure is from Telesco et al., 1982.

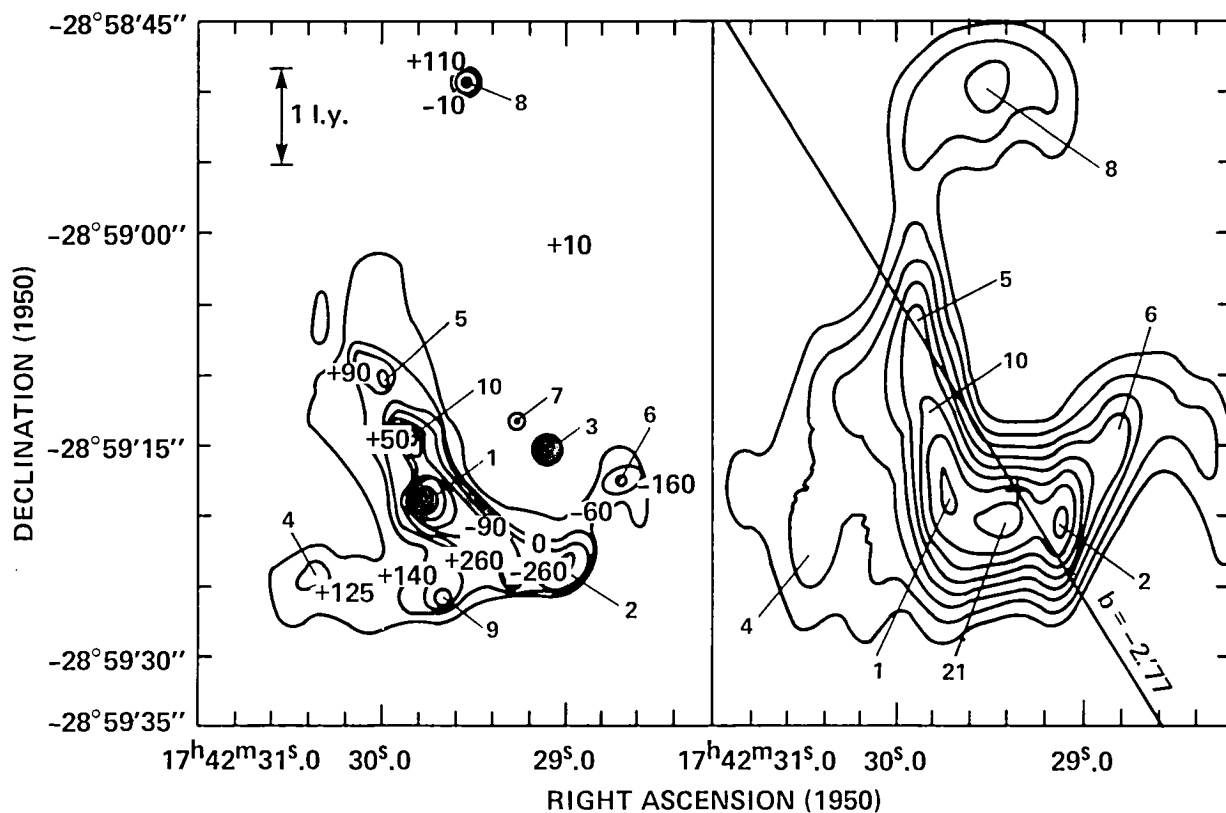


Figure III.4.— Center of the Milky Way Galaxy seen with 1 arcsec resolution in the near-IR and radio. The central ~ 10 l.y. of our Milky Way Galaxy is viewed in the near-IR (left) and radio (right) with resolutions of ~ 1 arcsec. The left map shows the 10- μm continuum of Becklin et al., 1978, superimposed with the velocities of the ionized gas clouds (large numbers) observed by the NeII (12.8 μm) transition (Lacy et al., 1980). The small numbers (with arrows) mark the IRS numbers of the continuum sources (warm dust). On the right is the high resolution VLA map of the 5-GHz emission with the non-thermal radio source (cross) removed (Brown et al., 1981). The interesting structure and dynamics of the central region is partially revealed by these high-spatial-resolution maps. Note that 30-arcsec resolution, typical of current far-IR telescopes, would encompass nearly the entire active region and would fail to resolve this structure.

abundances of heavy elements across a galaxy will trace variations in the rate of star formation or in the type of stars formed.

Elemental abundances are most easily determined in regions of ionized gas, where N, O, S, Ne, Ar, and other prominent species radiate fine-structure transitions in the near- and far-IR. The high angular resolution and sensitivity of the LDR allow measurements of abundances and the variation of abundances across typical galaxies (“abundance gradients”) out to a distance of 6×10^7 l.y. These abundance gradients have already been inferred from optical observations, but far-IR observations result in abundance determinations which are, by comparison, free from the effects of ionization structure, extinction by dust and temperature variations.

As an example of the sensitivity of a 20 m LDR, the O^{++} fine-structure line at $88 \mu\text{m}$ can be detected with 1-min integration in individual regions of ionized gas in galaxies as distant as those of the Virgo cluster. The cluster includes many types of spiral galaxies and the relationship between elemental abundances (star-formation rates) and galactic types can be studied there very profitably.

The stellar population of a galaxy can be studied by looking at broadband colors and by studying characteristic spectral features. Combining data from ST and LDR, the spectrum of a galaxy at $Z = 1$ can be measured from the ultraviolet Lyman limit to $2 \mu\text{m}$ in the rest frame. Many important diagnostic features in the ultraviolet, visible, and the near IR can be measured. With these data an accurate assessment of the relative population of young blue stars, old red giants, and old main sequence stars can be calculated. These data would permit determination of the history of starformation at the current epoch and in galaxies less than half the age of the Milky Way. Pushing this study to redshifts of $Z \lesssim 2$ is possible with long integrations. At these redshifts, almost all the features are beyond $1 \mu\text{m}$ and are best measured with the LDR (see discussion of 1- to $4\text{-}\mu\text{m}$ telescope sensitivities in appendix A and section III.C).

The gas and dust content of galaxies at redshifts $Z \cong 1$ can be measured by comparing the stellar light in the 1- to $4\text{-}\mu\text{m}$ range with the far-IR emission from dust and gas. The dust radiation is a broad continuum that peaks at about $100\text{--}200 \mu\text{m}$ in most galaxies, with a typical luminosity of $3 \times 10^9 L_{\odot}$. The gas in the interstellar medium emits strong far-IR lines, including about $10^8 L_{\odot}$ in the C^+ fine-structure line at $157 \mu\text{m}$. Both this line and the dust continuum can be measured by LDR in galaxies at $Z = 1$ in less than a day’s integration.

2. Star Formation in Giant Molecular Clouds

The giant molecular clouds (GMC) within our own Galaxy have been the subjects of great interest over the last decade. Ground-based radio observations have delineated their global properties (e.g., sizes approximately 100 l.y., masses approximately 10^4 to 10^5 solar masses, and average temperatures of 10 to 30 K).

To understand the evolution of these clouds, it is necessary to study the variation of these properties within a galaxy and from galaxy to galaxy. Angular resolution achievable with LDR will allow study of individual GMC at distances $\sim 3 \times 10^7$ l.y. (a region which includes approximately 100 galaxies) and the C^+ and C lines, as well as the rotational transitions of CO and other molecules will characterize the composition, density, and temperature of GMC as a function of distance from the centers of galaxies. Variations in the number of properties of GMC from one galaxy to another will provide needed information on the nature of star formation in different types of galaxies and may provide a long sought-after physical basis for galaxy classification schemes.

Within our own galaxy, studies have shown that molecular clouds do not simply contract to form stars. Rather, the areas of star-formation activity are concentrated in small regions of the GMC. These condensations are regions of enhanced density which often contain embedded infrared sources, evidence that star formation is already proceeding. These condensations range in size from 0.1 to 10 $\ell.y.$ (0.1 $\ell.y.$ corresponds to 40 arcsec at the distance of Taurus, the nearest GMC); some contain enough mass for one solar type star; others may form a cluster of perhaps 100 stars. The process by which these condensations actually form stars will be one of the primary foci of LDR research (see fig. II.4 reproduced here for easy reference).

Strangely enough, it has yet to be clearly demonstrated that any of the condensations we observe are collapsing to form stars at the present epoch. Any possible collapse motion is obscured by turbulent motion at size scales of $\gtrsim 0.1 \ell.y.$, which current instruments can resolve. Since we expect protostellar dust shells or disks to have dimensions of 10^{-4} – $10^{-3} \ell.y.$, collapse and rotation must become the dominant motions on scales between 10^{-3} to $10^{-1} \ell.y.$ (0.4 to 90 arcsec at Taurus), a regime which is currently inaccessible at the appropriate submillimeter wavelengths. Such shells or disks may result in the formation of binary stars – a very common phenomenon – or planetary systems. The 1-arcsec resolution of LDR corresponds to a physical scale of ~ 200 AU (about the size of the solar system) at Taurus, the nearest star-forming region, so that the collapse process can be followed into its final stages when the protostar and its associated disk are close to the size of the solar system (see fig. II.4).

In the decade before LDR can be launched, large millimeter wave antennas and interferometers will begin to explore this range of sizes. The principal limitation that these instruments face is sensitivity rather than resolution. Dissipation of turbulent or magnetic energy during the collapse should warm the protostellar environment to temperatures from 20–100 K. At such temperatures, the strongest emission from gas and dust would not be observable from the ground, being instead in the far-IR rather than in the millimeter region.

LDR observations of many spectral lines from the molecules will permit us to investigate the gas temperature, density, and velocity in the protostellar environment. In addition, observations of previously inaccessible molecules, like hydrides and H_2O , will yield entirely new kinds of information about chemistry in the protostellar environment. Chemistry can greatly affect the subsequent evolution into stars and planets. Magnetic fields must also play critical roles in retarding the collapse or in removing angular momentum in the later stages. Polarization measurements in the infrared indicate the orientation and structure of the magnetic field and even give crude estimates of the field strength. All these observations provide critical information for our understanding of protostar formation.

3. Formation of Protostars and High Velocity Flows

Although the LDR may not resolve the dust shells or disks surrounding forming stars,² LDR will provide critical new techniques for studying these regions which may ultimately form planets (see fig. II.4). First, the studies described in the last section will define the protostellar environment; second, a combination of emission and absorption lines studies can often reveal the properties and dynamics of structures such as a shell or disk on scales smaller than the telescope resolution.

Using LDR in a light-bucket mode at wavelengths shorter than $30 \mu m$, molecular vibration-rotation transitions can be seen in absorption against the “dust photosphere,” the region where the continuum is

²Spatial resolution of protostellar shells or disks will be possible using LDR as the first element of an interferometer, an eventual possibility for an evolving LDR.

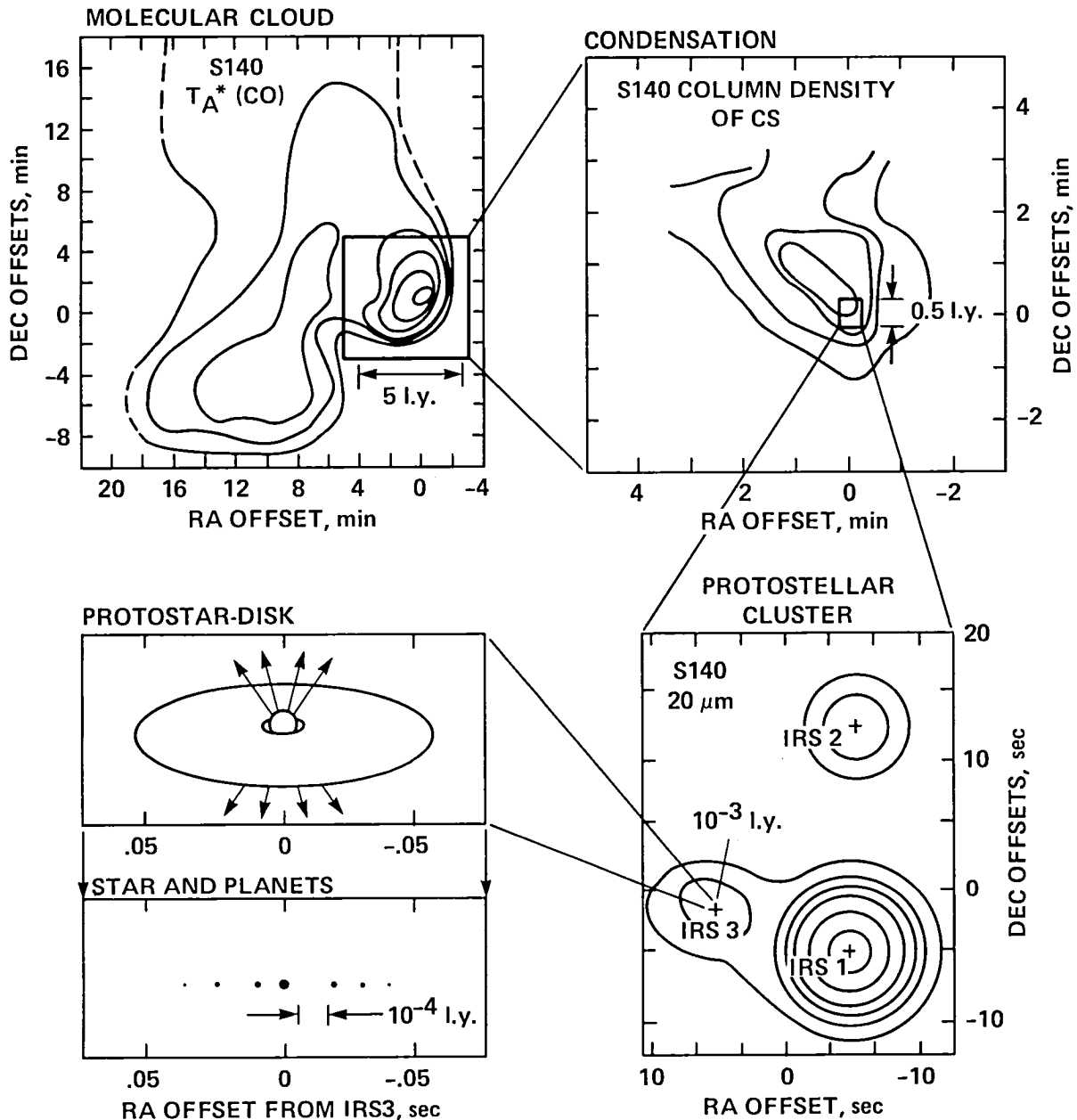


Figure II.4.— Collapse of an interstellar cloud to form a stellar system. At upper left is a map of the molecular cloud associated with S140 (Blair et al., 1978). The map was made in the $J = 1 \rightarrow 0$ transition of CO, an easily excited line which allows a map of the entire molecular cloud. Note that this map, which does not cover the whole cloud, extends for about 20 l.y. The box marks a region of star formation. This region was further studied using four transitions of CS (Snell et al., 1982). The column density of CS, displayed at the upper right reveals a dense condensation within the molecular cloud (typical density of 10^5 – 10^6 cm $^{-3}$). Within this dense condensation, a cluster of infrared and radio continuum sources has been found (Beichman et al., 1979), as shown at lower right. This map covers about 0.3 l.y. with a resolution approaching 0.015 l.y. If we could examine the region on still smaller scales (~ 0.001 l.y.), we might hope to study the process of formation of individual stars (shown schematically at the lower left). These stars are known to produce copious outflows of matter, often in a bipolar pattern, which may be produced by a protostellar disk. This system may in turn evolve into a star and planetary system like our own.

produced, giving an effective spatial resolution equal in size to the dust photosphere. With high spectral-resolving power, the velocity field can be deduced. For example, if the absorption lines were red-shifted with respect to the emission lines, which define the rest velocity of the protostellar system, we can deduce that the region producing the absorption lines is moving toward the protostar, presumably in a collapse. Because different vibration-rotation lines arise in different regions of density and temperature, we can hope to unravel the radial dependence of density, temperature, composition, and velocity field around the protostar.

Preliminary studies of this kind have been made on the brightest such object, the Becklin-Neugebauer object (BN). Surprisingly, these studies revealed outward motion through the blue-shift of the absorption lines. Other, less direct, methods now indicate that outflow is a nearly ubiquitous feature of protostellar regions. Presumably, these outflows are caused by a stellar wind which may end the growth of the protostar. The origin of the stellar wind is uncertain, but it may be related to the dissipation of magnetic energy or the outward transport of angular momentum, both processes which must occur if stars were to form. Many of the more extended flows are bipolar and confinement by accretion disks or other structures has been suggested (see fig. II.4).

The high velocity (~ 100 km/sec) outflows from the newly forming stars react strongly upon the remnant of the cloud from which the stars formed, producing shock-heated gas that can be studied in the far-IR. These interactions may have many important consequences: they may induce the formation of other stars within a cluster or they may inhibit it; they may provide the relatively steady energy input required to sustain the supersonic turbulence observed within large cloud complexes; and they may induce chemical reactions within the shock-heated gas that are important for the overall composition of the gas and grains. The Orion molecular cloud is the best studied example of these phenomena. On a 20 m LDR, the IR lines of shock-excited CO could be detected from a source like Orion at a distance of 10^8 l.y., a distance which includes the Virgo cluster, vastly improving our knowledge of the lifetime and likelihood of such energetic outflows.

Within the Milky Way Galaxy, the LDR, with a spatial resolution of 1 arcsec, can isolate the individual objects within a cluster of young stars, evaluate the effects which each has on its immediate environment, and search for additional stars forming within the cluster environment. These high angular resolution studies of clusters of young stars could also determine the luminosity and temperature of each cluster member and thus the mass distribution of the forming stars. In short, the combination of high spatial resolution and high spectral resolution, which will be possible for the first time in the far IR from LDR, will make it an essential tool for investigating the final stages of star formation.

The shocked molecular gas in the star-forming regions also provides an excellent opportunity to study elemental abundances because many lines will be excited which would otherwise be undetectable. For example, the rotational lines of HD at 112, 56, and $37\ \mu\text{m}$ may be used in conjunction with H_2 lines at shorter wavelengths to derive the HD/ H_2 ratio which reflects the cosmic D/H ratio, a very important quantity for cosmological models. The large size of LDR and the ubiquity of these shocked regions will allow studies of regions near the galactic center where stellar processing should have decreased the D/H ratio, and of regions farther out in our galaxy where D/H may reflect its cosmological value more closely.

4. The Origin of Planetary Systems

The bipolar nature of the outflow regions discussed above suggests a disklike geometry surrounding the protostar (see fig. II.4). If this disk structure occurs close to the protostar, it may be identified with the accretion disks which are thought to lead to the formation of planetary systems. This view reflects the consensus among astronomers that planetary system formation is a natural concomitant of star formation. To

test this conjecture, we have two possible approaches: a search for other planetary systems and a detailed study of our own solar system in an attempt to deduce the nature of its origin.

(a) *Extrasolar planet search*— The possibility of detecting extrasolar planets is one of the most exciting prospects in astronomy. The LDR has an advantage over direct detection of a planet at optical wavelengths because it can observe at wavelengths where the planet's emission is maximum (for Jupiter, $30\ \mu\text{m}$) and where the stellar emission is greatly reduced from the stellar peak. For the Sun/Jupiter case viewed from outside the solar system, the stellar/planetary ratio is about 10^4 at $30\ \mu\text{m}$, compared to 10^{11} at $0.5\ \mu\text{m}$. Assuming the imaging quality of the telescope is adequate, a 20-m LDR could detect (with a signal-to-noise ratio of 5) a Jupiter-like planet in approximately $10^{-2}\ d^4$ sec integration time, with the distance, d , to the planet in light years. As many as 50 nearby stellar systems could be studied in this search.

Angular resolution of $\lesssim 1$ arcsec at $30\ \mu\text{m}$ and low-angle scattering of the stellar component are required to resolve the planetary image. Less than 10^{-4} of the stellar signal should be scattered into a resolution element ~ 10 arcsec from the star. It should also be noted that unusual opportunities for planetary detection may exist with very young systems where internal planetary heat sources may be $\sim 10^4$ times stronger than the present Jupiter, and with very evolved systems such as white dwarfs where the stellar planetary ratio may be smaller.

(b) *Solar-system studies*— The origin and early history of the solar system is largely unknown in spite of the great leap in understanding the present solar system made possible by spacecraft. One of the major clues to the origin of the solar system lies in the variation of composition with distance from the Sun, especially for the planets and satellites in the outer solar system. The elements already detected in planetary atmospheres with direct and remote methods number < 13 , and the LDR can increase this known inventory of elements with high-resolution, far-IR spectroscopy. A better understanding of the compositional gradients in the solar system will help us to understand better the condensation sequence and physical environment of the early solar system.

The isotopic abundances of H, C, N, and O are incompletely known and we expect to be able to greatly increase our understanding of the isotope ratios in the outer solar system with LDR. We may hope to understand the nucleosynthetic history of the material out of which the solar system formed in this way. In addition, the comparison of various isotope ratios will be important in estimating the variation of isotope fractionation with distance from the Sun. For the outer planets, this should lead to an indication of the temperature gradient in the nebula from which the planets formed.

An important observation will be the composition of the “raw” material in comets, since comets are the most primitive objects in the solar system and they may provide a direct link to the chemistry in the protostellar disk. The ionized and photo-dissociated products have been observed to date but the “parent” molecules have not (although marginal detections of H_2O , CH_3CN , and HCN have been reported). Many of the expected parent molecules have strong far-IR transitions and LDR provides an opportunity to observe inner regions of the coma where the parent molecules are expected to have the greatest abundance. This will allow us to better understand the nature of the primordial solar nebula and the relationship of comets to the interstellar medium.

5. The Evolution of Planetary Atmospheres

LDR provides access to an exciting new spectral window within which it will be possible to investigate basic questions of fundamental importance in solar system research: What are the major processes that determine the composition of planetary atmospheres? To what extent are the atmospheres of the outer planets primordial? Can we isolate physical processes in primitive atmospheres that gave rise to the molecular

precursors of life? The search for molecular precursors of life is related to the question of what physical processes can give rise to life and how frequently life occurs in the galaxy. LDR therefore offers the potential of bridging the gap between solar system studies and the broader questions of stellar evolution and the origin of life in the universe.

Observations of planetary atmospheres have greatly increased in sophistication over the past decade so that very high spatial and spectral resolution is required to improve our understanding of the physical and chemical states of atmospheres. The physical parameters that need to be understood better, especially for planets not yet visited by probes, include the pressure-temperature profiles, the vertical and horizontal distribution of atmospheric constituents, internal heat sources, winds, and nonlocal thermal equilibrium processes in stratospheres. Knowledge of these parameters will immensely aid our understanding of the evolution of planetary atmospheres.

Pressure-temperature profiles are particularly important, providing the basis for the deduction of other physical quantities such as the distribution of gases with depth, thermally driven winds, atmospheric mixing, cloud formation, and seasonal changes. The far-IR is a particularly important spectral region since it allows us to probe the tropospheric region of atmospheres with its absorption lines in the continuum and the stratospheric regions with its emission lines, thus covering a range of 10^3 in pressure.

We anticipate many new far-IR stratospheric emission lines to be detected in the atmospheres of the planets and satellites. The emission lines will generally arise from molecules produced photochemically in the upper atmosphere and many radicals such as CH, CH₂, PH, and PH₂ in the stratosphere and upper troposphere. Molecules thought to play an important role in the formation of life, such as H₂O, CH₄, NH₃, HCN, and H₂CO, should be observed as well in the outer planets. Thus, the basic processes which are thought to have given rise to life on Earth will be available for scrutiny with LDR, in addition to basic chemical and photochemical processes in atmospheres.

LDR is particularly important for the studies described here because it will allow far-IR and submillimeter observations at unprecedented high spatial resolution (see fig. III.5) and also permits extremely high spectral resolving power (up to 10^7) observations. These capabilities are required to provide the follow-up work that should be done after reconnaissance by spacecraft.

6. The Death of Stars

Toward the end of their evolution, stars begin to lose matter, returning their outer layers to the interstellar medium whence they came. In many cases these layers have been enhanced in heavy elements mixed outward from the stars' nucleosynthetic cores. It is in these outflowing regions that the dust grains form. For some stars in this phase of evolution, the dust shell becomes so thick that the star disappears, hiding itself in a shroud of its own making. Such stars cannot long maintain their prodigious mass-loss rates (up to $10^{-4} M_{\odot} \text{ yr}^{-1}$) and must be nearing the end of their life.

The next stage may be a planetary nebula or, in rare cases, a supernova explosion. These processes inject nuclearly processed material back into the interstellar medium, laden with heavy elements formed in the stellar interiors or in the supernova explosion. Study of these objects will fill a critical gap in our knowledge of stellar and interstellar evolution. LDR will play a critical role in several aspects of this study.

The outflow region provides a rich chemical laboratory with conditions similar to those surrounding protostars, but with a more orderly and regular structure. Steady mass loss produces a density distribution that depends inversely on the square of the distance from the star. As a result, many decades in density can be studied in an orderly way. Studies of far-IR emission lines of CO, H₂O, and other molecules will be

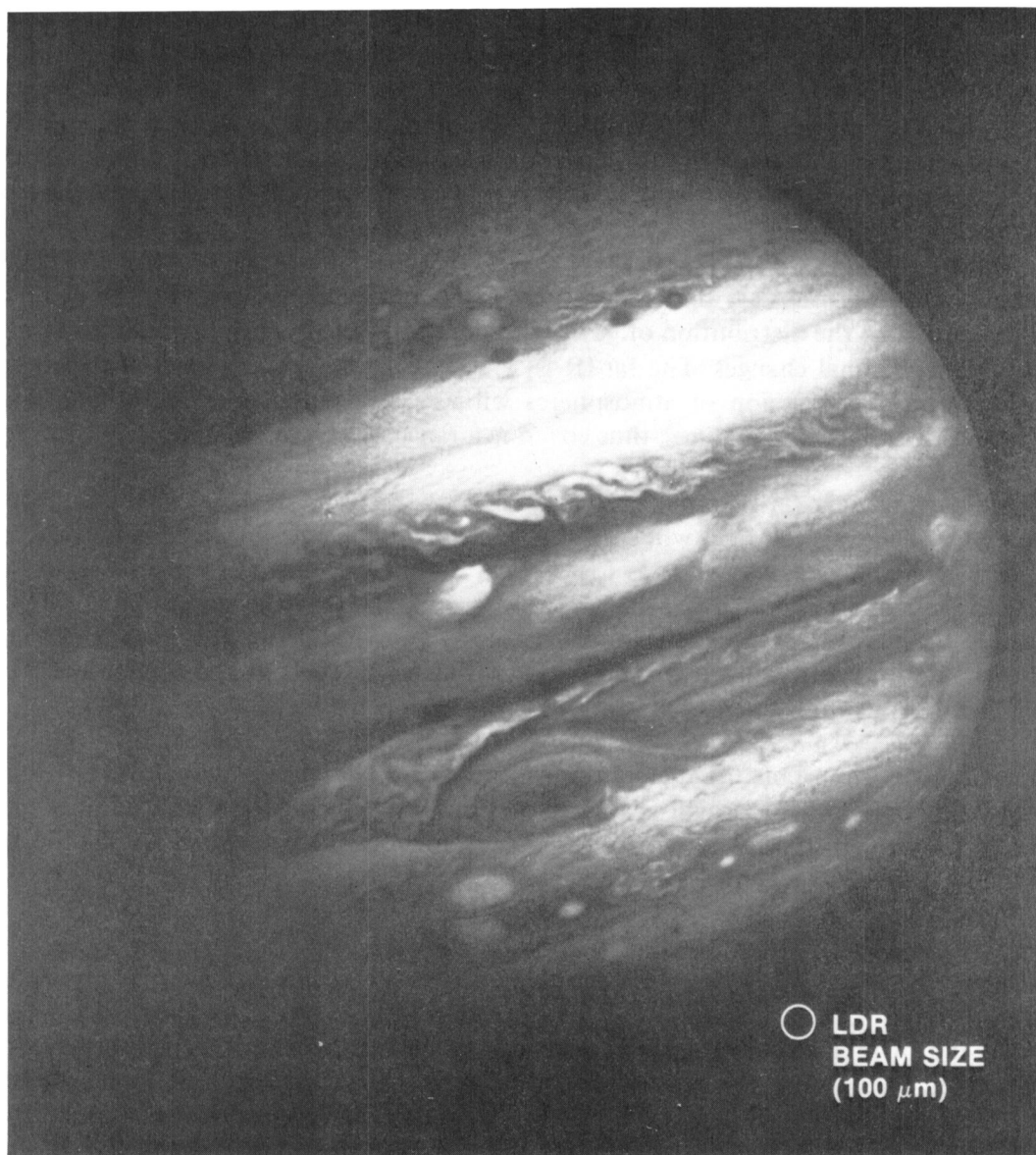


Figure III.5.— Angular resolution of LDR compared to Jupiter. Perhaps the origin of the color of the Great Red Spot will be discovered through high-resolution spectroscopic studies at the unprecedented high spatial resolution that LDR provides.

complemented by near-IR absorption spectroscopy of the inner portion of the dust shell against the star. As in the case of protostars, the combination of these techniques will allow the physical and chemical conditions to be deciphered on scales much smaller than the beam size of the telescope.

The formation of dust grains in these outflows is extremely important but poorly understood. The nature of the dust formed and the details of its formation can be explored with LDR. Spectroscopy at low resolving power ($R \sim 10^2 - 10^3$) in the far-IR and in the atmospherically opaque regions of the near-IR can tell us much about the nature of the dust and interferometric or lunar occultation techniques may be able to determine the radius, hence, density and temperature at which the dust forms. At typical distances of 300 l.y., angular resolutions of 0.1 arcsec near 10 μm would be required (see fig. III.6).

These outflows are also the sources of heavy elements brought to the stellar surface by convection. These products of nuclear processing are the ultimate source of the raw materials for molecules and dust grains in the interstellar medium. Submillimeter spectroscopy with a 1-10 arcsec spatial resolution offers the promise of revealing elemental and isotopic abundances for the key nucleosynthetic elements, C, N, and O.

The average abundances over the shell would be very revealing, testing theories of stellar structure. Radial variations in isotopic abundances may occur as a result of drastic episodes in the advanced evolution (e.g., a helium flash). In the most extreme cases, a substantial fraction of the original mass of the stars will be exposed for investigation. Observation of variations in the radial abundances in the flow will provide a history of the convection and nucleosynthetic processes in the original star.

These mass outflows may provide much of the gas and dust in the present interstellar medium. For an accurate assessment of the role these stars play, it will be necessary to obtain detailed spectral information on these objects over a substantial portion of the galaxy, a goal achievable only with an instrument like LDR.

C. COSMOLOGY

1. Small-Scale Fluctuations in the Cosmic Background

The condensations of matter which now form galaxies and clusters of galaxies are gravitationally bound systems that contracted from a more uniform distribution early in the evolution of the universe. The theory for the evolution of small-density contrasts predicts that density fluctuations of amplitude $\Delta\rho/\rho \approx 10^{-4}$ were needed at redshift $Z \approx 1500$ to become the current galaxies and clusters of galaxies. These density fluctuations would have interacted with the cosmic background and produced temperature fluctuations in the present 3 K background temperature with amplitudes $\Delta T \approx 10^{-4}$ K.

The spectral variation of the received power due to a fluctuation ΔT in the cosmic background is shown in figure III.7. There is very little power at wavelengths shorter than 500 μm , so the only way to obtain good spatial resolution is to have a large telescope. For a 20 m LDR operating at 1 mm wavelength all angular scales >10 arcsec are accessible, while SIRTf can only do angles >4.5 arcmin. Thus SIRTf will be the best telescope for fluctuations on scales from 5-20 arcmin, and LDR will be best for angles <5 arcmin. LDR will have further advantage as a permanent observatory of being able to perform very long integrations. For example, a ΔT of 1 μK will be measurable in 10^6 sec, about 2 weeks.

The apparent size of the expected fluctuations depends on the masses of the condensations and the cosmological model. For example, density fluctuations with the mass of clusters of galaxies would have an angular radius of <5 arcmin for a cosmological model with a deceleration parameter $q_0 < 0.5$ and a Hubble

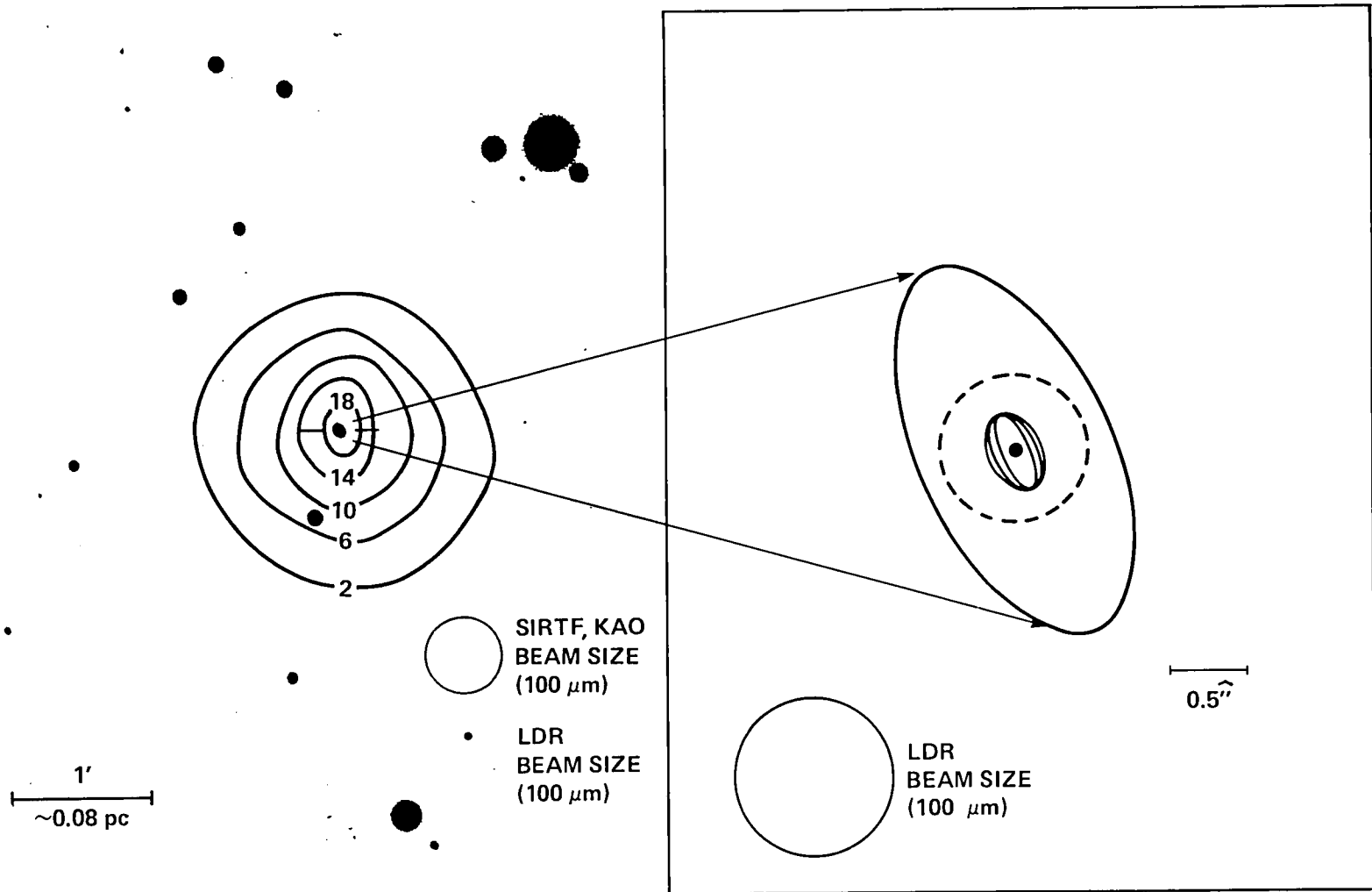


Figure III.6.— Mass outflow region in IRC+10216. On the left, an optical photo (Becklin et al., 1969) of the evolved carbon star IRC+10216 is shown. The nebulosity is caused by light scattered off dust grains formed in the outflow from the dying star. On the right is an enlarged diagram of the structure of the outflow, as inferred from near-IR interferometry (McCarthy et al., 1980). The outflow has been observed in CO to extend to approximately 3 arcmin from the source (Knapp et al., 1982). The contours in the left figure are peak antenna temperatures for the $J = 2 \rightarrow 1$ transition of CO, as mapped by Wannier et al. (1979). LDR can map and identify spectral features in the dust and gas component out to such distances.

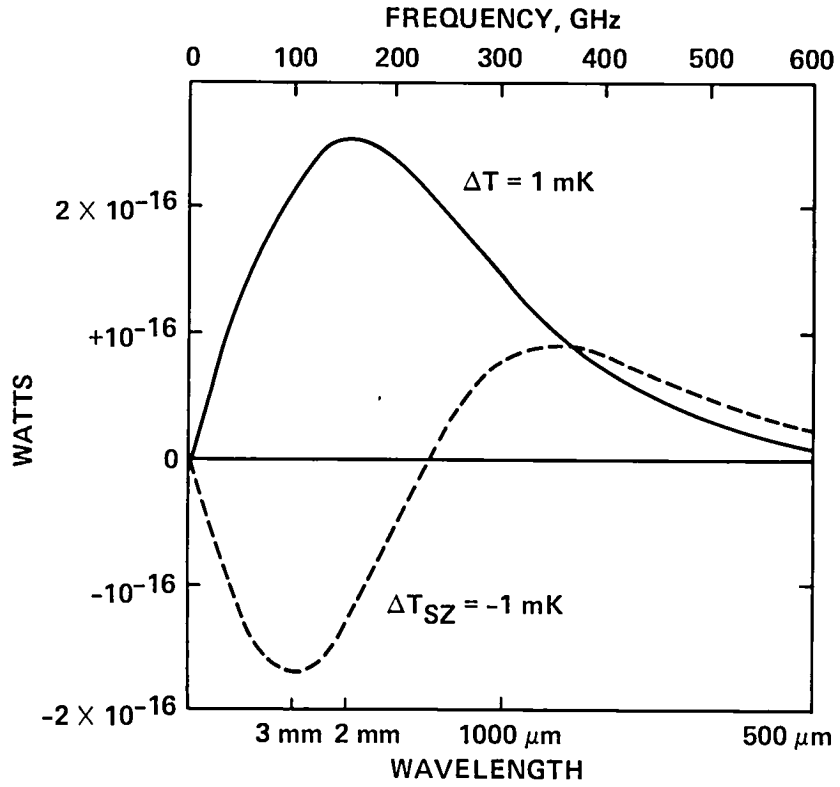


Figure III.7.— Deviations in the microwave background. Power in a diffraction-limited beam for $\Delta\nu/\nu = 0.1$. Solid curve: a $\Delta T = +1$ mK temperature change. Dashed curve: Sunyaev-Zeldovitch effect with $\Delta T_{SZ} = -1$ mK at low frequencies. Note that the Sunyaev-Zeldovitch effect reverses sign near 1 mm wavelengths so that submillimeter observations with the LDR will provide a crucial signature of this effect.

constant $H_0 = 100$ km/sec/Mpc, while clumps with the mass of galaxies have a radius of about <1 arcmin. It is clear that the high angular resolution of the LDR will be needed for these measurements.

Larger ground-based telescopes operating at 3 mm wavelength will also be able to measure ΔT . To date, these ground-based studies have not been sufficiently sensitive because of water-vapor fluctuations in the atmosphere, but new receivers that simultaneously measure on and off a waterline have been able to eliminate this noise source. Even though ground-based telescopes should give the same sensitivity to ΔT as LDR, figure III.7 shows an important reason for observing shorter wavelengths from space.

Compton scattering off hot electrons, which are known to exist in clusters of galaxies and may pervade all intergalactic space, produces a distortion in the cosmic background shown as ΔT_{SZ} (for Sunyaev and Zeldovitch) in figure III.7. Data at two wavelengths are needed to distinguish this cause of background fluctuation from that associated with inhomogeneities in the early universe. An ideal pair of wavelengths for this test are 3 and 1 mm. A 20-m LDR at 1 mm will give the same angular resolution as 60-m ground-based telescopes at 3 mm.

One very important application of the Sunyaev-Zeldovitch effect will be to directly measure the rate of expansion of the universe given by the Hubble constant H_0 and the deceleration given by the parameter q_0 . This will be done by comparing ΔT_{SZ} in a cluster of galaxies with X-ray measurements of the same cluster. This method requires accurate measurements of ΔT_{SZ} , the X-ray flux, the X-ray temperature, and the angular distribution of the source. High angular resolution measurements are needed to minimize the effects of clumping of the electrons. The LDR at 500 μm will give better than 10 arcsec resolution, while AXAF working in the X-ray will give even better resolution.

Combining LDR data and AXAF data should allow a determination of H_0 to $\pm 20\%$ that is completely independent of all the calibrations of the stellar distance scale. Such an independent test is very important for verifying our cosmological models and for estimating the age and eventual fate of the universe.

2. Starlight from Faint Galaxies

The structure of space and time in the neighborhood of the Milky Way has been mapped through studies of galaxies. Ever since Hubble discovered the redshift-distance law, galaxies have provided the primary signposts marking the geography of the universe. In the decades after Hubble, galaxy counts have been used to establish the homogeneity of the universe on very large scales, the redshift-magnitude law has been pushed to redshifts Z of about 0.5, and galaxy clusters have been used to study the inhomogeneity of the universe on small scales. All of these studies have been limited to $Z = 0.5$ by the bright optical sky and the reduction in intrinsic brightness as the redshift brings the faint ultraviolet emission from galaxies into the optical band.

But LDR, located above the OH nightglow, with its large, cool, collecting area allowing operation in the zodiacal light minimum at 3 μm , will be able to find and study galaxies at $Z > 3$. By observing in the IR, LDR will gain a sensitivity advantage as the bright 1 μm emission from high- Z galaxies is redshifted into the passband. In fact, LDR will see galaxies to such great distances that the sky will be covered with overlapping images of galaxies: over 1,000 galaxies/min², with an average Z close to 3.³

Figure III.8 shows the number of galaxies expected for various flux levels at 3.2 μm , plotted against redshift. LDR will be able to reach these flux levels in $<10^4$ sec (about 1 hr) of integration time even for

³ Because the $N(S)$ curve is quite flat at this flux, the signal to confusion ratio is 3:1 for 3.6 beams per source, corresponding to a 1 arcsec beam.

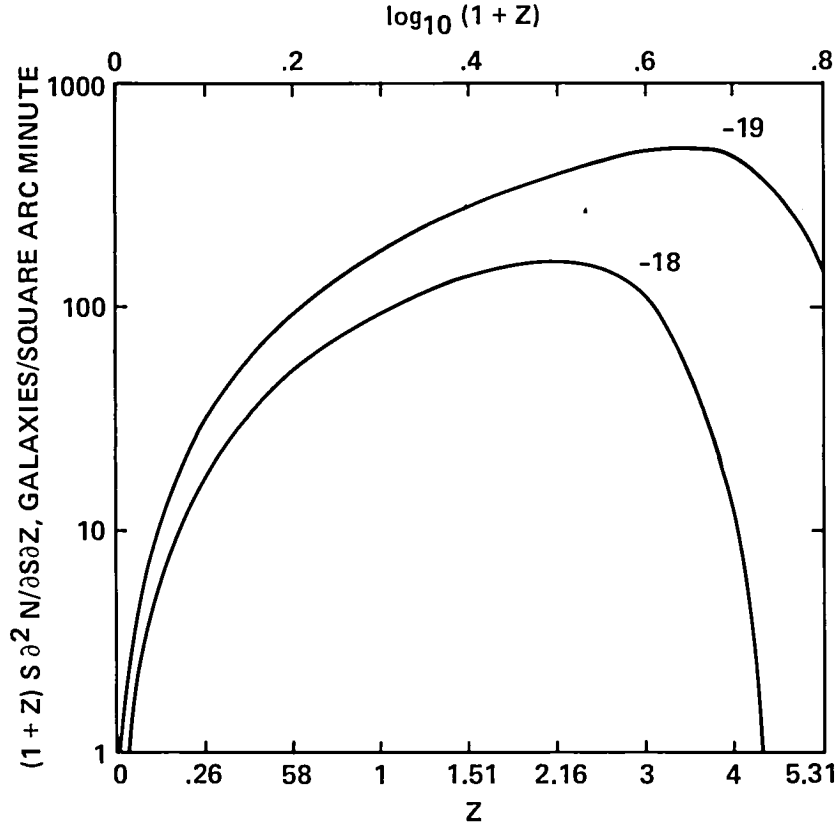


Figure III.8.— Differential distribution of the galaxies visible in logarithmic intervals of $(1 + Z)$ and flux at $3.2 \mu\text{m}$. Curves are labeled with $\log_{10} (S = \nu F \text{ Wm}^{-2})$, and calculated for $q_0 = 0$. LDR can reach these flux levels in $<10^4$ sec of integration time with currently available detectors and 20-m diam. Angular resolution of $\lesssim 1$ arcsec is required to minimize source confusion.

currently available detectors and a 20 m diam. No other existing or proposed telescope can match LDR performance here: ST and ground-based telescopes are too warm, giving excessive backgrounds. Ground-based telescopes also see the OH night-glow which is 500 times as intense as the zodiacal light. ST is much smaller than LDR, while SIRTf is even smaller, thus lacking sensitivity in this spectral region where all cold IR space telescopes are limited by detector noise.⁴

Two wavelength imagery from LDR will allow the use of color as an approximate redshift indicator. Color becomes a third dimension, besides angular correlation, to identify cluster membership. Cluster contrasts may be improved more than 10 times, allowing cluster identification out to $Z = 3$ or 4. Spectroscopy of brightest cluster galaxies, again done by LDR, would extend the redshift-magnitude diagram for brightest cluster galaxies out to $Z = 3$ or 4. The other standard cosmological tests, such as cluster size versus redshift and number versus magnitude, would all be extended to a Z range five or six times greater than currently available.

Since cosmological tests require determination of curvature in these diagrams, LDR will give data 30 times better than currently available. Furthermore, since LDR is looking at radiation from the typical stars in a galaxy, unlike optical telescopes which must look at the unusual blue and ultraviolet stars, the effects of evolution on the cosmological tests will be much less.

The LDR is therefore the ideal telescope for studying galaxies at the "red limit." The only limitations will be the inherent astrophysical limit set by overlapping galaxy images. Since galaxies are intrinsically fuzzy, angular resolution much greater than 1 arcsec is not useful. No telescope will ever be able to see more distant galaxies than an LDR with 1 arcsec angular resolution at 2–4 μm and mirror temperatures of 200 K or cooler.

⁴LDR is detector-noise limited with detector noise equivalent power (NEP) of 10^{-17} W/Hz^{1/2}. SIRTf would need a detector NEP of 6×10^{-20} W/Hz^{1/2} to be background-limited. With such good detectors, 500 times better than the current state of the art, SIRTf could do the proposed science, but LDR would still be more sensitive.

IV. SUMMARY OF KEY TELESCOPE AND INSTRUMENT REQUIREMENTS FROM THE SCIENCE RATIONALE

A. TELESCOPE REQUIREMENTS

Table IV.1 outlines the telescope requirements imposed by the performance needs of the scientific rationale detailed in section III. We summarize below some of the key scientific considerations which resulted in these requirements.

TABLE IV.1.— GENERAL TELESCOPE REQUIREMENTS

1. Diameter	≥ 20 m
2. Shortest wavelength of diffraction-limited performance (λ_c)	30–50 μm (see text)
3. Light bucket blur circle	$\lesssim 2$ arcsec at 1–4 μm
4. Temperature and emissivity	Primary $\lesssim 200$ K, $\epsilon = 0.01$ at $\lambda = 1$ mm, $\epsilon = 0.05$ for $\lambda \lesssim 1$ mm
5. Chopping	2 Hz, 1 arcmin (reactionless)
6. Sidelobes	Low near sidelobes (see text)
7. Scan	1° by 1° — Linear scan at $1^\circ/\text{min}$
8. Slew	$\geq 50^\circ/\text{min}$
9. Field of view	≥ 3 arcmin
10. Absolute pointing, jitter	0.05 arcsec, 0.02 arcsec

1. Diameter

A 20-m telescope produces a diffraction limited spatial resolution of ≈ 1 arcsec at 100 μm , a resolution which allows direct comparison with ground-based optical measurements. Figures II.3, II.4, and III.1–III.6 dramatically demonstrate the utility of such spatial resolution. Galaxies at cosmological distances are of this size, as are spiral patterns in distant galaxies, giant molecular clouds in nearby galaxies, nearby collapsing protostars in our own galaxy, planet-star separations in the closest stars, and the Great Red Spot on Jupiter.

A second important consideration is in the sensitivity of LDR to point sources. The distance to which LDR can detect such objects is proportional to its diameter D and, if the objects are uniformly distributed, the number of objects that can be studied goes as D^3 . A 20-m telescope is sensitive to Jupiter-like planets out to ≈ 10 l.y., to star formation regions and elemental abundances out to the Virgo cluster of galaxies (where correlation with galaxy type can be made), and to cosmologically distant galaxies ($Z = 1$ for the CII (157 μm) line and $Z \approx 4$ for the starlight in the near IR).

2. Shortest Wavelength of Diffraction-Limited Performance λ_c

One overall consideration which indicated $\lambda_c = 30$ μm was a desire to maintain diffraction-limited performance to the onset of atmospheric windows at 30 μm . Typically, star-formation regions look smaller as one views with shorter wavelengths which probe the hotter cores. A $T \approx 100$ K blackbody spectrum peaks at about $\lambda \approx 30$ μm and the outer regions of a planetary system or a preplanetary disk can be expected to have temperatures of this order and arc-second to subarc-second sizes.

Clearly, the highest spatial resolution at $30\ \mu\text{m}$ is warranted. For studies of nearby solar planets, and the molecule HD (the $J = 3 \rightarrow 2$, $37\ \mu\text{m}$ line is potentially one of the strongest) in the galactic center, a diffraction-limited beam at $\lambda \approx 30\ \mu\text{m}$ is also important. Diffraction-limited performance to $\lambda \lesssim 30\ \mu\text{m}$ will be required for good light-bucket capabilities in the near IR.

However, the Science Workshop concluded that if major gains could be made in telescope diameter or major reductions could be made in the telescope cost, λ_c could be increased somewhat to $50\ \mu\text{m}$ if the $30\text{-}\mu\text{m}$ blur circle did not appreciably exceed the $50\text{-}\mu\text{m}$ spot size.

3. Light-Bucket Blur Circle

Important fine-structure emission lines in the $5\text{--}30\text{-}\mu\text{m}$ wavelength region, vibrational absorption lines in the $1\text{--}10\text{-}\mu\text{m}$ region, and spectroscopic features of grains in the $1\text{--}30\text{-}\mu\text{m}$ region all argue for a light-bucket capability of LDR with a blur circle of approximately 2 arcsec; the strongest argument for such capability arises in the cosmological study of highly red-shifted galaxies, which require a blur circle of 1 to 2 arcsec at $2\text{--}4\ \mu\text{m}$ in order to avoid significant source confusion. This cosmological study was considered the most important of the “light-bucket” problems.

As shown in appendix A, the size of the light-bucket blur circle has a dramatic effect on sensitivities shortward of λ_c .

4. Temperature and Emissivity

The telescope temperature primarily affects the light-bucket performance at $1\text{--}5\ \mu\text{m}$, where the thermal background is extremely sensitive to telescope temperature. LDR will be detector-noise limited for $\lambda < \lambda_{\text{max}}$ where $\lambda_{\text{max}} = 2.8$ and $4\ \mu\text{m}$ for $T = 200\ \text{K}$ and $150\ \text{K}$, respectively, if $R = 10$ and detector $NEP \approx 10^{-17}\ \text{WHz}^{-1/2}$ (see appendix A). The strongest case for low temperature is made for the cosmological problem mentioned above where every increase of λ_{max} by $1\ \mu\text{m}$ allows the faint galaxy study to be extended deeper in the universe by a $\Delta Z \approx 1$.

Lowering the emissivity ϵ of the telescope is the best way to lower the background in the Rayleigh-Jeans wavelength range $\lambda \approx 1\ \text{mm}$. Therefore, the lowest possible emissivities (~ 0.01) are called for in this wavelength region.

5. Chopping

Spatial chopping will be needed on LDR to permit cancellation of telescope background emission by rapidly switching the astrophysical targets in and out of the beam of the telescope. This technique, invariably used by IR astronomers, has made it possible to detect sources at the level of 10^{-6} or less of the background flux. The considerations governing the use of chopping on LDR will be very different from those to which IR astronomers are accustomed because the sources of background are different for LDR than for a ground-based IR telescope. A further discussion of chopping on LDR is presented in the companion volume.

6. Sidelobes

One of the most stringent requirements on sidelobes comes from the search for extrasolar planets, where the $30\ \mu\text{m}$ flux in a 1 arcsec beam positioned 10 arcsec from a strong source (a star) can only include $\lesssim 10^{-4}$ of the stellar signal.

7. Scan

The LDR is, in part, a mapping instrument and nearby large molecular cloud complexes and galaxies are of the order 1° in size. Furthermore, the scan may be used in effect to chop with an extremely large throw for these very extended objects. The required scan performance is also needed to track comets and planets in the solar system.

8. Slew

The slew rate is dictated by the desire to move from one object in the sky to another (typical distance $\sim 120^\circ$) in a time short compared with an orbital viewing (~ 20 min).

9. Field of View

At minimum, one would like a field of view equal to the diffraction-limited resolution of the KAO or SIRTf, $\sim 30 (\lambda/100 \mu\text{m})$ arcsec, so that arrays could image these fields. LDR will be, in part, an imaging device and numerous objects (e.g., planets, condensations in molecular clouds and HII regions, and galaxies) have sizes of order 1–10 arcmin. At the longest wavelengths the FOV should at least include several resolution elements.

10. Absolute Pointing and Jitter

The astronomical rule of thumb is that jitter should be ~ 0.1 of the beam size, which is ~ 0.5 arcsec at $30 \mu\text{m}$, to optimize long integrations on point sources.

B. INSTRUMENT REQUIREMENTS

1. Scientific Investigations

The scientific investigations described in section III cover a broad range of objects, ranging from bright, nearby planets to faint distant galaxies, QSOs, and fluctuations in the cosmic background radiation. The instruments required for these studies also cover a broad range of capabilities ranging from photometric imaging arrays to ultra-high resolving-power spectrometers. An overview of the requirements can be seen in figure IV.1, where key studies and experiments are indicated on a plot of resolving power ($R = \nu/\delta\nu$) versus frequency.

A comparison of figure IV.1 with figure II.7 will reveal that the scientific studies described in section III primarily exploit the superior sensitivity of LDR over SIRTf for spectroscopy. The photometric ($R \sim 3\text{--}10$) observations recommended for LDR either exploit the enhanced sensitivity of LDR for both very long ($\lambda \gtrsim 200 \mu\text{m}$) and very short ($\lambda \lesssim 4 \mu\text{m}$) wavelengths or they exploit the superior angular resolution achievable in the far IR. The importance of 1 arcsec angular resolution has been illustrated in figure II.1 and discussed throughout sections II and III.

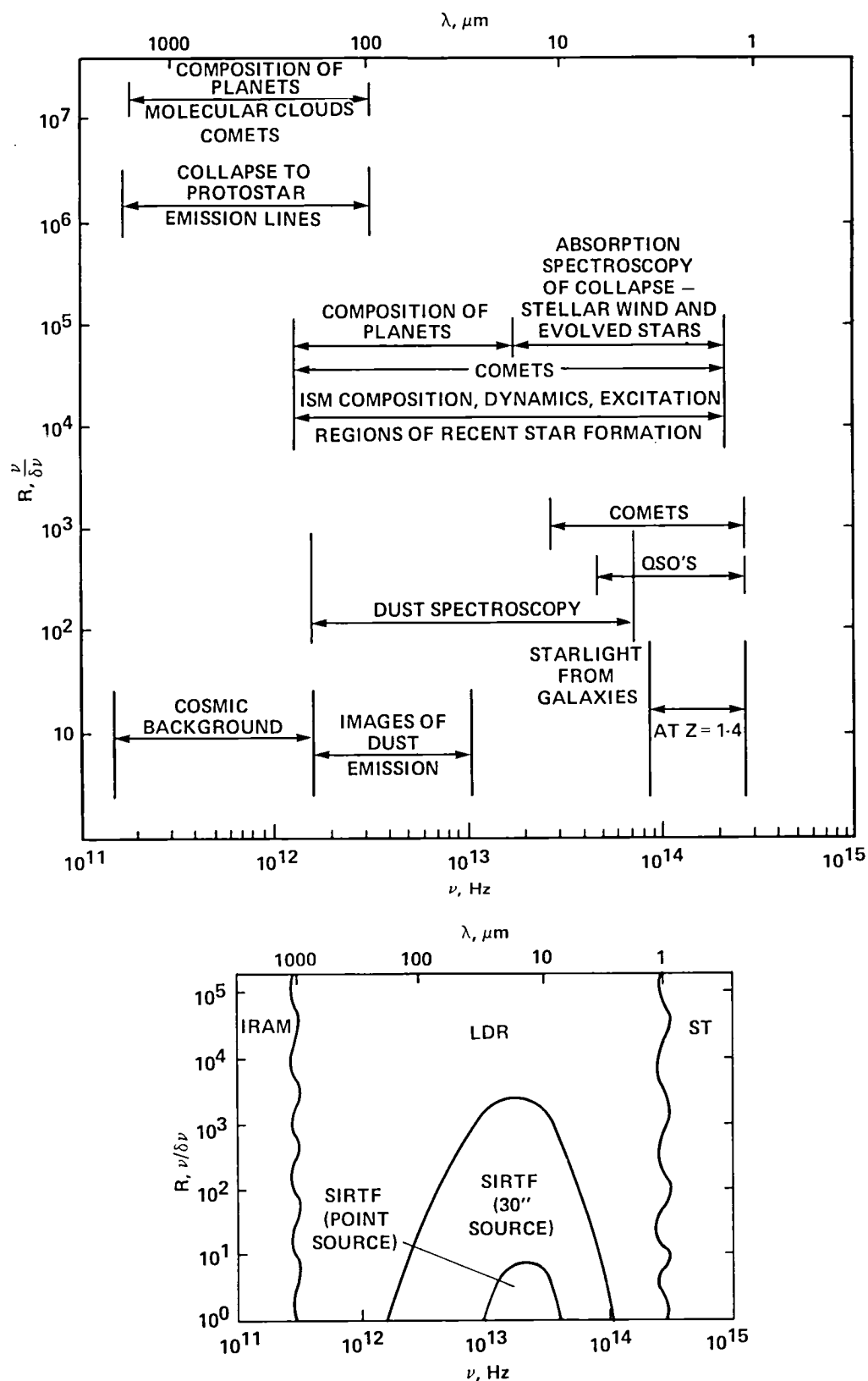


Figure IV.1.— Observational studies are plotted versus required spectral resolving power R and frequency (bottom) or wavelength (top). Note that nearly all of the studies fall in the region where LDR is more sensitive than other instruments (see fig. II.7).

2. A Strawman Instrument Complement

Table IV.2 contains a strawman instrument complement for LDR. The scope of the scientific investigations summarized in figure III.1 translates into an extremely broad range of instruments. Some order can be found by grouping the instruments by resolving power. Within each regime of resolving power, several instruments will be required to cover the wavelength range of interest. Because the exact nature of many of the instruments has not been established, we will refer to them by generic identifiers. In the order of increasing resolving power, we have the Photometric Imaging Array with $R = 3-10^2$ and four arrays to cover the required wavelength range, the Medium Resolving Power Spectrometer with $R = 10^2-10^3$ and three arrays or single detectors, the High Resolving Power Spectrometer with $R = 10^4-10^5$ and three arrays or single detectors, and finally, the Ultra-High Resolving Power Spectrometer with $R = 10^6-10^7$ and three heterodyne front ends.

The large number of instruments will make it important to find ways to share common elements. For example, the three heterodyne front ends in the Ultra-High Resolving Power Spectrometer will share common backend electronics. Some of the photometric arrays might also be used for spectroscopic devices. Despite these possible economies, table IV.2 clearly represents a technological challenge. Continued interaction between the astronomers and technologists will be essential for assigning appropriate priorities and assessing technological possibilities.

TABLE IV.2.— LDR STRAWMAN INSTRUMENT COMPLEMENT

I. Photometric imaging array ($R = 3-10^2$) – arrays, filters, filter wheels, polarimetry			
$\lambda_{\text{range}}, \mu\text{m}$	Detectors	NEP, ($\text{W}/\text{Hz}^{1/2}$)	Scientific investigation
A. 1–5	In:Sb, Si:In 100X100 array	5×10^{-17}	Galaxies at $Z = 1-4$
B. 30–120	Ge:Ga 100X100 array	10^{-17}	Star-formation regions, dust emission
C. 100–200	Stressed Ge:Ga 40X40 array	10^{-16}	Star-formation regions, other galaxies
D. 100–1000	Bolometer 10X10 array	10^{-16}	Star-formation regions, cosmic background, radiation
II. Medium resolving power spectrometer ($R = 10^2-10^3$) – gratings, fts, arrays			
A. 1–5	In:Sb, Si:In 1d or 2d array	10^{-17}	QSO Comets
B. 5–30	Si:As, Si:Sb, Si:P	10^{-16}	Comets, dust spectroscopy
C. 30–120	Ge:Ga 100X100 array	10^{-16}	dust spectroscopy
III. High resolving power spectrometer ($R = 10^4-10^5$) – gratings, fts, Fabry-Perot			
A. 1–5	In:Sb, Si:In 1d array or single detector	10^{-17}	Absorption spectroscopy, emission in HII regions, shocked regions
B. 5–30	Si:As, Si:Sb, Si:P 1d or single detector	5×10^{-17}	Gas in star-formation regions and planets, HII regions
C. 30–220	Stressed Ge:Ga	10^{-17}	Gas in star-formation regions and planets, HD/H ₂ ratio

IV. Ultra-high resolving power spectrometer ($R = 10^6-10^7$) – heterodyne receivers (SIS, Schottky, or bulk)				
λ_{range}	T_{sys}	Lines (examples, μm)		Regions of study
A. 521–654 μm (460–575 GHz)	100	NH ₃ $J_K = 1_0 \rightarrow 0_0$ CH $^2\pi_{3/2}J = 3/2 \rightarrow ^2\pi_{1/2}J = 1/2$ CI $^3P_1 \rightarrow ^3P_0$ CO $J = 5 \rightarrow 4$ $4 \rightarrow 3$	524 μm 561 μm 610 μm 521 μm 651 μm	Star-formation regions, collapse to protostars, evolved stars, comets
B. 361–455 μm (660–830 GHz)	200	H ₂ O $J_{K-1}K_1 = 1_{01} \rightarrow 0_{00}$ H ₂ S $J_{K-1}K_1 = 1_{01} \rightarrow 0_{00}$ CI $^3P_2 \rightarrow ^3P_1$ CO $J = 6 \rightarrow 5$ $7 \rightarrow 6$	429 μm 421 μm 370 μm 434 μm 372 μm	
C. 110–157 μm (1.91–2.73 THz)	500	HD $J = 1 \rightarrow 0$ CII $^2P_{3/2} \rightarrow 2P_{1/2}$ SiI $^3P_1 \rightarrow ^3P_0$ OI $^3P_0 \rightarrow ^3P_1$ CO $J = 17 \rightarrow 16$ to $J = 24 \rightarrow 23$	112 μm 157 μm 130 μm 145 μm 160 μm 110 μm	

V. FUTURE PLANNING OF THE LDR

At the Asilomar workshop most of the scientific and technical goals were discussed and, to some degree, evaluated. One result of the interaction between scientists and technologists was the development of three possible technical scenarios for LDR. It was also clear that progress depends on continuous interactions between astronomy and technology representatives, to make sure that these scenarios would be properly evaluated and that the preferred solution be effectively developed and refined. Finally, there was unanimous agreement that the evolving project would demand careful ground and flight testing of various technologies and components. In this section, the science members of the Asilomar workshop make their suggestions for some necessary overall components of a plan to develop LDR.

A. THE SCIENCE WORKING GROUP

In informal discussions which took place throughout the workshop there was a strong consensus in favor of the formation of a Science Working Group whose main tasks would be:

- a) Advising NASA headquarters and centers on the continuing problem of optimizing the LDR design to meet the science goals.
- b) Evaluating the results of the current technical development program.
- c) Advising on requirements for additional ground and spaceflight technical programs (including instrumentation).
- d) Updating the science goals and maintaining a link to the wider national astronomy community.

B. THE THREE TECHNOLOGY SCENARIOS

A major difficulty in producing a plan for technical development of LDR is that there is not yet sufficient information available to evaluate the various possibilities. Although considerable progress has been made in the Ames/JPL studies carried out to date, it became clear at Asilomar that other concepts would have to be considered. The overall status of the technology appears to indicate that there are three routes which should be followed until one emerges as clearly superior. They are the following:

- a) A high-quality, multipanel, glass-type mirror system of circular aperture, to be deployed in space;
- b) A glass-type mirror system of rectangular (slot) shape, to be carried fixed within the shuttle bay;
- c) A multipanel, metal or composite reflector of circular aperture, to be deployed in space. We briefly discuss these from the astronomer's viewpoint.

1. Circular-Aperture Glass Reflector

If there were no cost, time, or technological constraints, this would be the system of choice, since the surface accuracy would be high enough to achieve all the science goals, even those in the light-bucket regime

(1–4 μm). The difficulties are in achieving sufficiently light, thin, stiff, accurate, and thermally stable panels without grossly exceeding reasonable weight, shuttle space, and cost budgets. Further problems exist, for instance, in deployment technology. The option of significantly reducing the aperture, while retaining the surface accuracy does not meet the science goals, because high angular resolution and large collecting area are dominant requirements in the 100 μm regime, the designated prime wavelength range for the instrument.

2. Slot Glass Reflector

It was clear at the workshop that one of the major problems for LDR is the deployment of the mirror. The system is inevitably to be made of panels and these might have to be assembled in space, together with the backup structure, by astronauts or mechanical manipulators. Alternatives, such as unfolding designs, were not favored. All of these deployment schemes are complex and expensive; therefore, it was suggested that the problem could be avoided by changing the shape of the reflector from circular to rectangular, so that a slot-shaped mirror of about 18 m (shuttle-bay length) by 4 m (shuttle bay width) could be launched in assembled form.

Various difficulties with this approach were noted. From a technical point of view it appears that the double curvature of the mirror will take up the shuttle-bay space in an awkward way, leaving little useful space for packing the remainder of the telescope and the instruments, which would still have to be deployed in any case. From a scientific viewpoint, there would be a loss of performance due to the reduced area and somewhat reduced resolution. This slot would also have to be rotated to synthesize a circular aperture, for most observations. For certain observations which do not require the highest angular resolution, this is inefficient. In some cases (e.g., planetary) this might not be practical because of the rapidly changing aspects of the object under study.

The possibility of extending the slot, say to 36 m by 4 m, was discussed. This would have the advantage of increasing the angular resolution, but would involve some deployment.

Overall, the slot mirror was considered inferior to a filled 20-m aperture and its potential problems listed above may warrant further study.

3. Circular-Aperture Metal/Composite Reflector

Current technical wisdom suggests that simple metal (aluminum) honeycomb panels could be used for LDR to provide a mirror with a weight of less than 20 kg/m^2 , which would be well within the shuttle-constrained value for a 20-m reflector. The problem with this solution is that it has not yet been demonstrated that the surface would be adequate for wavelengths shortward of 100 μm . Also, there would be thermal-control problems, since metals have relatively large thermal expansion coefficients. Use of composite materials such as graphite-epoxy alleviates the latter problem, but perhaps not sufficiently, and may be difficult to attain a reflecting finish. However, the costs would be lower and the availability of space for instruments in the shuttle bay greater.

The availability of this approach is most important since it is an already demonstrated technology which could accomplish some of the major goals of LDR. It could not, however, accommodate the light-bucket observations in the 1–4- μm range, without considerable further development.

C. TECHNICAL EVALUATION

Returning to the question of how to proceed in the evaluation of these options, it seems best to continue studies on all three if possible, but certainly on the glass and metal, circular-aperture models. The slot model can always be reconsidered using data obtained from studies of the other models. Now that a reasonably well-defined science specification exists, it may be practical to make detailed evaluations of each option against those specifications. While it was already clear that a major development requirement existed in the area of panel construction, the workshop pointed out several other areas in need of basic development, e.g., deployment technology (the instrumentation point is taken up in the next section).

A point which received unanimous support in the workshop, and which arose on several occasions, concerns flight testing of the component technologies. There are several critical technologies, which, in many cases, must be flight tested, no matter which option is chosen. The testing could be in the form of small shuttle packages in some cases, but in others it may involve a larger effort. Areas of particular concern include panel thermal behavior, active panel control, deployment technology, and instrumentation (see next section).

D. INSTRUMENTATION

Since many astronomers are involved in the development of IR detectors and spectrometers, they have a strong direct interest in the anticipated instrumentation for LDR. They are keenly aware of deficiencies in the present technology and would like to assist in the planning for the future, particularly through the Science Working Group mentioned previously.

At the workshop it was noticed quite early that there had been little thought on the question of LDR instruments. For instance the system F number has a serious impact on the instruments and could make instrument construction impossible unless care is taken. The large size of LDR will force the use of large instruments if the optics are not carefully thought out. The initial result seems to be a requirement for a small primary F number. Similarly, the size of the instruments has to be taken into account in the payload. Large instruments would be difficult to accommodate and deploy and would be expensive to construct.

From appendix A it can be seen that the anticipated detector NEPs make a vital impact on the telescope design in the area of temperature control and emissivity. Lower NEPs require lower temperatures and emissivities. The whole instrument capability (for some applications) is basically determined by the available detectors.

As a result of these and other considerations it seems necessary to make a special effort in instrumentation planning and development, early in the LDR pre-project time line. Instrumentation planning and development are just as important as the telescope structures work even at this early stage. Just as in the case of the panel technologies, it will be necessary to flight-test some of the detector systems. There have been virtually no heterodyne receiver tests in space in the wavelength range of LDR. For example, the proposed detectors may well be radiation sensitive. Such tests could be flown along with major panel tests activities, or they could be small, separate projects using the Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN), for example.

In summary, the scientists at Asilomar envisioned several important steps which would be elements in the evolution of a successful LDR project. One step would be the establishment of a continuing Science Working Group whose tasks are outlined above. A second step provides for careful evaluation of two or three

overall design concepts for the LDR. Another step involves the development and testing of critical technologies such as panel construction, telescope deployment, and instrumentation.

The major goal of the scientists at Asilomar was the development of an initial science rationale for the LDR. The bulk of this document details the important astrophysical observations that could be made with the LDR, particularly in the fields of star and planet formation and cosmology. These observations allowed a quantitative estimate of many technical design features on the LDR such as surface emissivities, telescope temperature, and chopping, slew, and tracking parameters. In addition, the scientific rationale altered preconceptions on the overall design of the LDR. Instead of a minimum 10-m diam telescope, diffraction-limited to a wavelength of $30\text{ }\mu\text{m}$, the scientists argued for a minimum 20-m diam telescope, diffraction-limited to $30\text{--}50\text{ }\mu\text{m}$ and which hopefully would maintain a blur circle of less than 2 arcsec at wavelengths as short as $2\text{ }\mu\text{m}$ – a technical challenge for the coming decade!

The LDR represents an instrument of major scientific importance as well as a significant departure in design and philosophy. It will be the first observatory to be erected and possibly assembled in space. Building this enormous telescope should provide invaluable lessons in the construction of large high-precision structures in space; the LDR may therefore be the forerunners of giant, optical astronomical facilities in space. The participants in the Asilomar workshop felt that the willingness on the part of the scientific community, NASA, and the public to commit significant resources toward meeting the challenges and possibilities of space astronomy represented an eloquent expression of the best in our society.

APPENDIX A

SENSITIVITY OF LDR AND OTHER INFRARED DEVICES

A. BACKGROUND

The background power onto detectors depends on the emissivities and temperatures of the background sources. The astronomical background sources are the zodiacal light, scattered sunlight and thermal emission from galactic dust, scattered galactic starlight, unresolved stars, and cosmic background. In addition, the telescope emits with some emissivity and temperature. For ground-based telescopes there is also the airglow, which is primarily from OH in the IR.

The zodiacal light is normalized to $100S_{10}$ in the visible, i.e., 100 10th magnitude stars deg^2 . The spectrum of the scattered light follows B_ν (5500), where B_ν is the Planck blackbody intensity. The model thermal emission has a peak νI_ν which is 5.5 times higher than the scattered light, or an albedo of 0.15 for the dust. The thermal emission is modeled as the sum of two different temperatures, each with emissivities $\epsilon\alpha\nu$, whose sum looks like a 300 K blackbody near the peak of νI_ν . The emissivities and temperatures for this three component model of the zodiacal light are given in table A.1.

TABLE A.1.— ZODIACAL LIGHT MODEL

Zodiacal light	ϵ	T, K
Scattered sunlight	5.77×10^{-14}	5500
Hot dust	$2.80 \times 10^{-7} / \lambda(\mu\text{m})$	285
Cold dust	$1.78 \times 10^{-6} / \lambda(\mu\text{m})$	197

The OH airglow measured at Kitt Peak in May of 1982 by zenith scans is about 8×10^7 Jy/sr at 1.6 and 2.2 μm , and fell to about 4×10^7 Jy/sr at 1.25 μm .

Given the emissivities $\epsilon_i(\nu)$ and temperatures T_i of the background sources labelled by i , we first calculate the intensity I_ν at the detector by an iterative process beginning with the most distant source of background, the cosmic background, where $T_0 = 3$ K and B_ν is a Planck intensity function.

$$I_\nu^0 = B_\nu(T_0)$$

Then, for each successive background source of temperature T_i and emissivity $\epsilon_i(\nu)$, we compute the transmission $\tau_i(\nu)$ and resulting intensity, I_ν^i , by

$$\tau_i(\nu) = 1 - \epsilon_i(\nu)$$

$$I_\nu^i = \tau_i(\nu) I_\nu^{i-1} + \epsilon_i(\nu) B_\nu(T_i)$$

repeating this process, until the detector is reached. Since the emissivities associated with the galactic dust, the zodiacal light, the OH nightglow, and the telescope mirrors are all small, one can approximate the intensity at the entrance aperture of the cold instrument as

$$I_{\nu}^{in} = B_{\nu}(T_0) + \sum \epsilon_i(\nu) B_{\nu}(T_i) + I_{\nu}^{OH}$$

The optics inside the instrument will normally be so cold that its contribution can be ignored. If so, we only need to know τ , the total transmission of the cold optics, and the intensity at the detector is

$$I_{\nu}^d = \tau I_{\nu}^{in}$$

Now compute the average number of photons per mode,

$$\bar{n}(\nu) = \frac{I_{\nu}^d}{2h\nu(\nu/c)^2}$$

Note that lossless optics do not change I_{ν} . Thus, lenses, mirrors, and light pipes can be ignored except for their reflection losses. Even immersion optics do not change \bar{n} , since in a medium with index of refraction m , the intensity increases by m^2 but $(\nu/c)^2$ increases by the same factor. Now the background power is computed using

$$dP_b = A\Omega I_{\nu}^d d\nu$$

where A is the telescope area and Ω is the beam solid angle; the background limit induced photon noise (BLIP) noise equivalent power (NEP) is computed using

$$NEP_b = \left\{ \int \frac{2h\nu[1 + \bar{n}(\nu)] dP_b}{\eta} \right\}^{1/2}$$

where η is the detector quantum efficiency (which is 1/2 of the carriers/photon for a photoconductor because of recombination noise).

For the simple case of $T_0 = 0$, warm optics temperature T with emissivity ϵ , and $\nu/\Delta\nu \gg 1$ where $\Delta\nu$ is the bandwidth of radiation falling on the detector, we find that

$$I_{\nu}^d = \frac{\epsilon\tau 2h\nu(\nu/c)^2}{(e^{h\nu/kT} - 1)}$$

$$\bar{n}(\nu) = \frac{\epsilon\tau}{e^{h\nu/kT} - 1}$$

A diffraction-limited beam gives $A\Omega = \lambda^2$ and

$$NEP_b = \left[4\eta^{-1} \Delta\nu (h\nu)^2 \left(\frac{\epsilon\tau}{e^{h\nu/kT} - 1} \right) \left(1 + \frac{\epsilon\tau}{e^{h\nu/kT} - 1} \right)^{1/2} \right]$$

for a detector that senses both polarizations. A coherent detector only senses one polarization, so that the 4 becomes a 2.

Generally, $\epsilon\tau \ll 1$. Only if $h\nu/kT \ll \epsilon\tau$ can one obtain the radio astronomy limit (for $\eta = 1$ and polarizations = 1):

$$NEP_b = \epsilon \tau k T \sqrt{2 \Delta \nu}$$

This agrees with the Dicke radiometer formula

$$\Delta \tau = \frac{T_{sys}}{\sqrt{\Delta \nu \Delta t}}$$

for $T_{sys} = \epsilon \tau T$, which is the actual brightness temperature on the detector (remember that NEP is defined for a 1 Hz bandwidth which gives $\Delta t = 1/2$ sec by the Nyquist formula).

There is a region where $\epsilon \tau \ll h\nu/kT \ll 1$. In this region NEP_b is given by

$$NEP_b = [4\eta^{-1} \Delta \nu \epsilon \tau (kT)(h\nu)]^{1/2}$$

for two polarizations. The equivalent system temperature is

$$T_{sys} = \sqrt{\epsilon \tau \frac{h\nu}{k}}$$

for $\eta = 1$, which is less than the “quantum limit” $T_{sys} = h\nu/k$. Since the quantum limit does not apply to direct detectors, this result is reasonable.

B. SENSITIVITY

For the final sensitivity calculation combine the detector noise NEP_d with the background noise giving

$$NEP = (NEP_d^2 + NEP_b^2)^{1/2}$$

Figure A.1 shows the BLIP NEP for typical LDR backgrounds. For $5 < \lambda < 250 \mu\text{m}$ detectors with $NEP_d = 10^{-16} \text{ W/Hz}^{1/2}$ will be background-limited.

The NEP can be used to compute a Noise Equivalent Line Flux (NELF) by

$$NELF = \frac{K(NEP)}{A\tau(1 - \epsilon)}$$

where K (typically $\sqrt{2}$) accounts for the background subtraction process. The NELF indicates the minimum line flux required for a signal to noise of one in a 1-sec integration. It is appropriate for assessing detectability of lines (high R) or broadband continuum fluxes (low R). For line work, one assumes that the line is inherently unresolved, or that adjacent channels are averaged to produce this situation. This is the optimum condition for detecting a line, but no information about line width or shape is available.

To consider studies of line profiles, one should use the Noise Equivalent Flux Density (NEFD), which is also commonly used to characterize continuum instruments. The NEFD is derived from

$$NEFD = \frac{NELF}{\delta \nu}$$

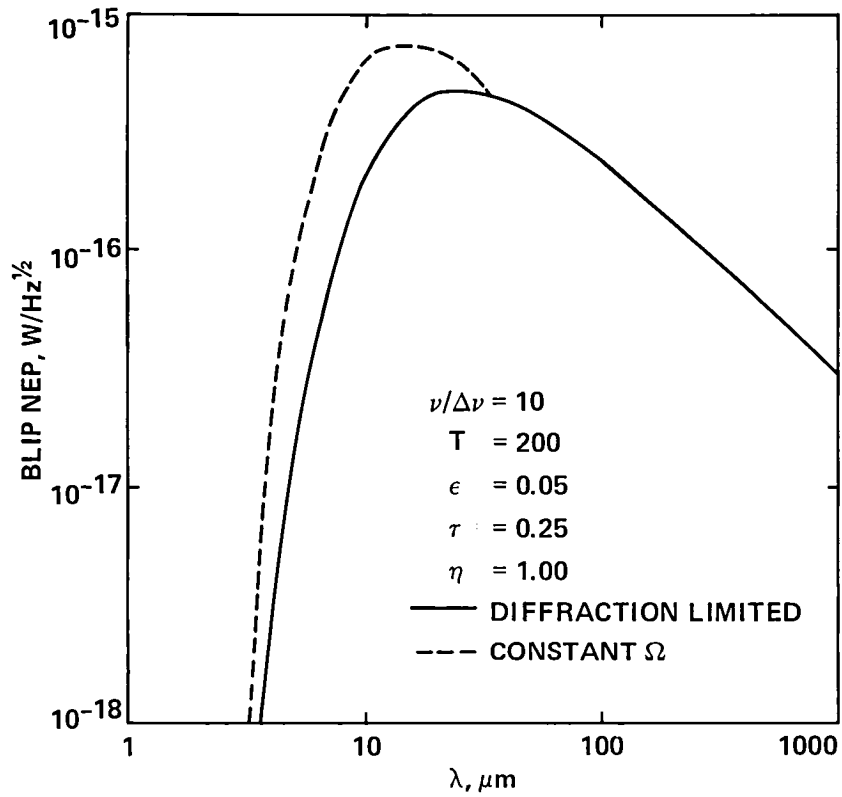


Figure A.1.— The background limit induced photon noise equivalent power (BLIP NEP) is plotted versus wavelength for an LDR with the following parameters: resolving power $(\nu/\Delta\nu) = 10$, ambient temperature 200 K, emissivity $\epsilon = 0.05$, total transmission $\tau = 0.25$, and detector quantum efficiency $\eta = 1.0$. The solid line assumes diffraction-limited throughout the wavelength band; the dashed lines assume diffraction-limited to $30\ \mu\text{m}$ and a constant beam size for $\lambda < 30\ \mu\text{m}$.

where $\delta\nu$ is the resolution. Note that $\delta\nu \neq \Delta\nu$ for some devices, like Fourier Transform Spectrometers and most heterodyne systems, but we will ignore this and assume $\Delta\nu = \delta\nu$ for these calculations. We characterize the calculations by resolving power, $R = \nu/\delta\nu$.

We have calculated the NELF (Wm^{-2}) and NEFD (Jy) for the LDR and for three other telescopes. Comparisons of different telescopes can only be made when telescope and detector parameters are known. Table A.2 lists telescopes and detector parameters assumed for the four telescopes, LDR, SIRTf, ST, and the University of California Ten Meter Telescope (UCTMT), a 10 m ground-based telescope. Rather optimistic detector NEP were assumed at all frequencies ($\text{NEP}_d = 10^{-17} \text{ W/Hz}^{1/2}$); these are important for LDR only at $R \gtrsim 10^4$ and in the near-IR, but they are critical in evaluating SIRTf. Diffraction-limited beams were assumed at all $\lambda > \lambda_c$. The blur circle for LDR was assumed to change abruptly at $30 \mu\text{m}$ from 0.3 to 2 arc-sec and then to remain constant (which is unrealistic, but represents the worst case in some sense). For the other telescopes the blur circle was assumed to remain constant for $\lambda < \lambda_c$ at the diffraction-limited value at λ_c except for the ground-based telescope, where $\theta = 1 \text{ arcsec}$ was set as the minimum. The emission and transmission of the atmosphere are included for the UCTMT.

TABLE A.2.— TELESCOPE AND DETECTOR PARAMETERS

Parameters	LDR	SIRTf	ST	UCTMT
D, m	20	0.85	2.4	10
$\lambda_c, \mu\text{m}$	30	5	.5	50 ^a
$\theta_{LB}, \text{arcsec}^b$	2	.6	---	1
T, K	200	10	250	270
ϵ	.05	.05	.05	.05
$\text{NEP}_d, \text{WHz}^{-1/2}{}^c$	10^{-17}	10^{-17}	10^{-17}	10^{-17}
η	.5	.5	.5	.5
τ	.25	.25	.25	.25
K	1.41	1.41	1.41	1.41

^aThis was set to insure that $\theta_{LB} \geq 1 \text{ arcsec}$.

^b θ_{LB} is the “light bucket” beam size assumed for $\lambda < \lambda_c$.

^cFor $R = 10^6$, heterodyne receivers were assumed, with $T_{\text{sys}} = 100 \text{ K}$ for $\lambda > 500 \mu\text{m}$ and $T_{\text{sys}} = 200 \text{ K}$ for $\lambda < 500 \mu\text{m}$.

Figure A.2 shows the results of the sensitivity calculations for the four telescopes, presented as NELF versus ν . Care has been taken to make the axes the same for all four plots. The same comparison is made for NEFD in figure A.3, but the ordinates differ in these plots. The LDR was assumed to have a temperature of 200 K. It is clear from these figures that LDR is superior to the three other telescopes at all λ between 1 and $1000 \mu\text{m}$ (the limits of the calculation) and $R \gtrsim 10$. It should be noted that these calculations assume a diffraction-limited beam, and hence, are relevant for unresolved sources. For extended sources, the smaller telescope will fare much better.

The effects of telescope temperature and light-bucket blur circle are illustrated in figure A.4, where a NELF plot is given for $T = 150 \text{ K}$, as well as for 200 K. The movement of the “wall” of background noise to longer wavelengths when the telescope is cooled is readily apparent. At 150 K, the window of low NELF extends to about $4 \mu\text{m}$, whereas it only extends to $2.8 \mu\text{m}$ at $T = 200 \text{ K}$. The other two figures show the effect of improving the light-bucket performance. In these calculations, the beam was assumed to remain

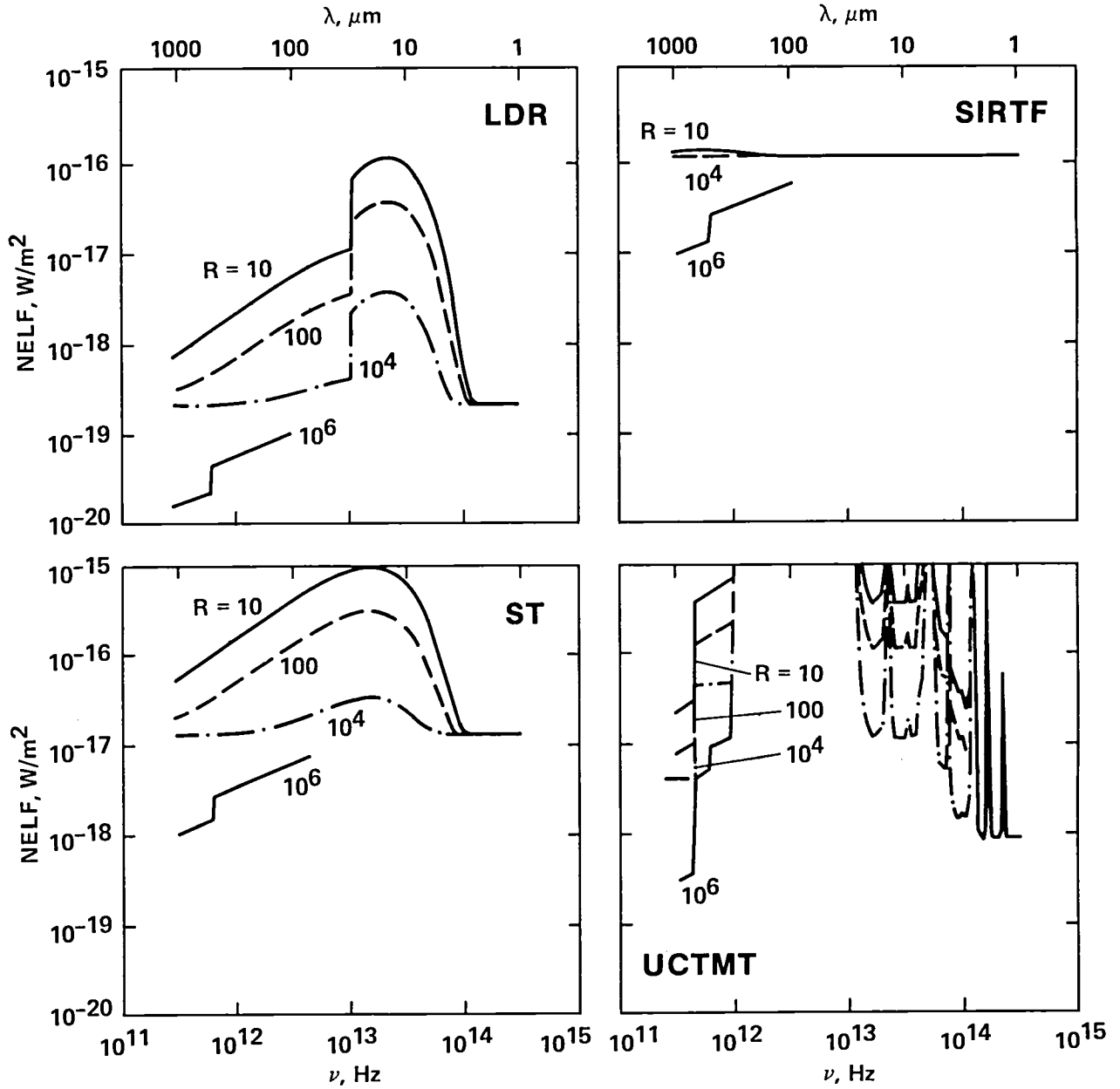


Figure A.2.— NELF of LDR, SIRTf, ST, and UCTMT vs wavelength. The sensitivity of LDR is compared to three other telescopes. NELF (W/m^2) is plotted vs frequency, with wavelength marked on the top. The resolving power ($R = \nu/\delta\nu$) is indicated by each curve. For the UCTMT, the transmission and emission of the atmosphere have been included; offscale regions indicate wavelengths where the atmosphere is essentially opaque. For comparison to radio astronomy units, the noise equivalent integrated width is $T_R \Delta\nu (\text{K km s}^{-1}) = 4.4 \times 10^{21} \text{ NELF} / \nu (\text{GHz})$ for a 20-m telescope in the diffraction limit.

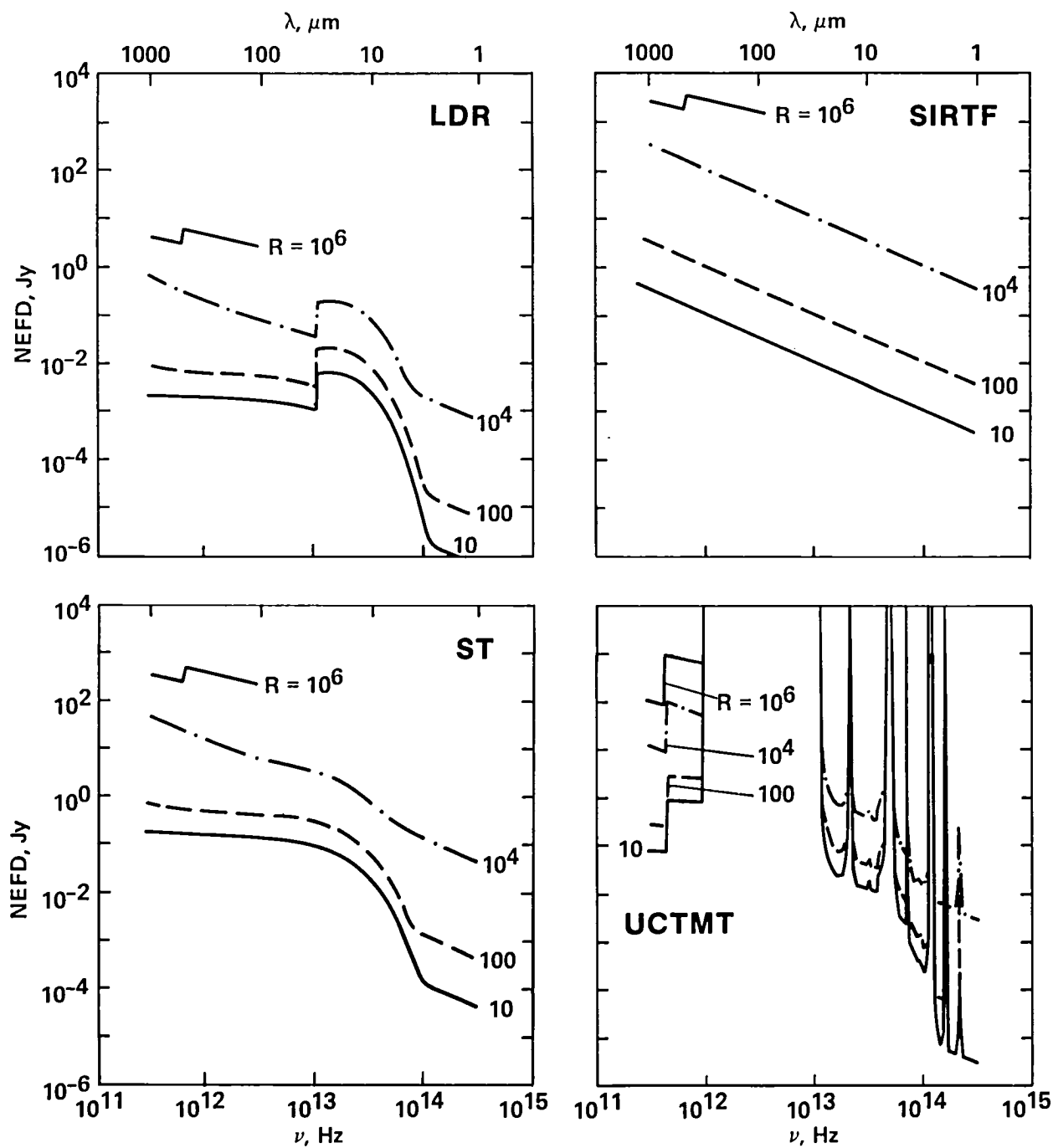


Figure A.3.— NEFD of LDR, SIRTf, ST, and UCTMT vs wavelength. As in figure A.2., LDR is compared to three other telescopes, but NEFD (Jy) is the measure of sensitivity. For comparison to radio astronomy units, the noise equivalent radiation temperature is $T_R = 0.14 \text{ NEFD}$ for a 20-m telescope in diffraction limit.

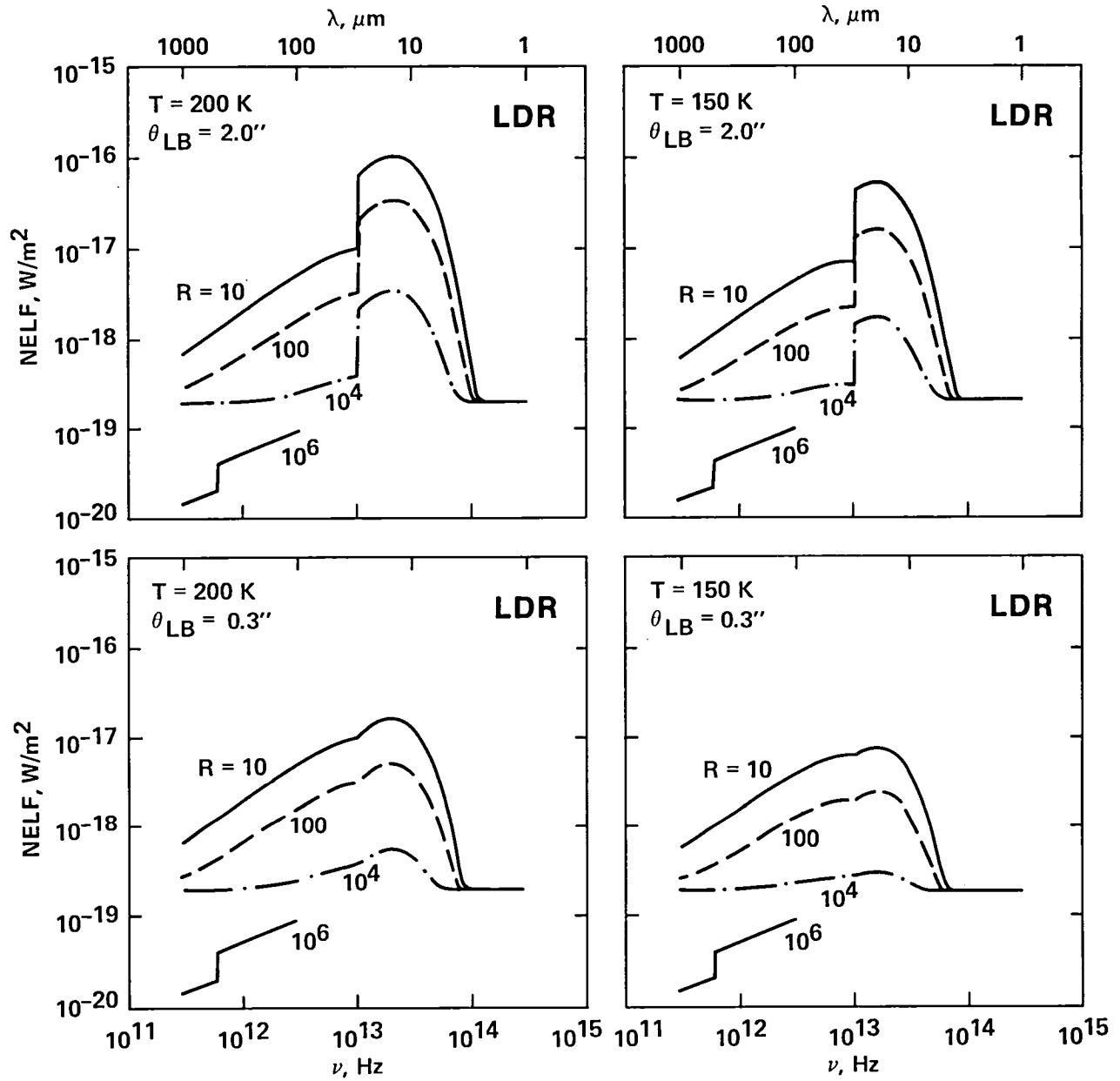


Figure A.4.— Effects of temperatures and light-bucket operation on LDR sensitivity. The effects of temperature and light-bucket beam size (θ_{LB}) are shown. Panel (a) is the case used in figures A.2 and A.3 and in the text: $T = 200$ K and $\theta_{LB} = 2$ arcsec. Panel (b) is for $T = 150$ K and $\theta_{LB} = 2$ arcsec. Panel (c) has $T = 200$ K and $\theta_{LB} = 0.3$ arcsec and Panel (d) has $T = 150$ K and $\theta_{LB} = 0.3$ arcsec.

constant at 0.3 arcsec, the diffraction limited value at $30\text{ }\mu\text{m}$, for $\lambda < 30\text{ }\mu\text{m}$. A substantial improvement in the mid-IR is seen as the background is reduced.

The fact that LDR is background-limited under most conditions means that more modest constraints are placed on detector NEP. For example, at $R = 10$ a detector NEP of $10^{-16}\text{ WHz}^{-1/2}$ would be adequate for between 3.7 and $300\text{ }\mu\text{m}$. Even for $R = 10^4$, such detectors would be adequate for λ between 8 and $30\text{ }\mu\text{m}$.

APPENDIX B

ANTHOLOGY OF LDR SCIENCE

At the workshop the science group was divided into sections working on various aspects of LDR astronomy. Those sections were: stellar evolution, interstellar medium, solar system, extragalactic studies, cosmology.

The text of the report covers the most important aspects of the science, in the view of the group chairmen and those responsible for writing the report. However, individual views vary somewhat, so that it was decided to list all the topics thought to be of importance. That list is recorded in this appendix. Also on file is a set of summary forms.

A. STELLAR EVOLUTION

a) Determination of the properties of the inner molecular and dust photosphere (or cocoon) of a collapsing protostar. This will be performed over the whole range of LDR diffraction-limited wavelengths (30–600 μm), with about 1 arcsec resolution.

b) Observation of inner disk structures in forming protostellar nebulae. This would require very high angular resolution at the LDR wavelengths, probably requiring an interferometer structure addition to LDR which could be provided at some later date.

c) Observation of the early stages of protostellar evolution in the dense cores of molecular clouds, which result in the formation of single stars, binaries, or clusters. This stage precedes a) and b) and involves slightly larger scales and lower temperatures ($\sim 10^{17}$ cm and ~ 50 K).

d) Mapping of dust continuum and study of kinematics of gas in the cores of high mass loss, young stellar objects. This stage of stellar evolution is somewhat later than a), b), and c) and involves hot, luminous, active regions. Again all LDR wavelengths are needed with angular resolution down to 1 arcsec.

e) Observations of the dust clearing phase. The clearing will appear to propagate from millimeter, through submillimeter, to IR wavelengths. Again 1 arcsec resolution is required with the eventual use of an interferometer being desirable.

f) Detection of preplanetary condensations in protostellar disks. Maximum possible resolution is needed in the 50 μm range.

g) Observations of young planetary systems in nearby stars. Possibly, the Hyades stream stars could be used. Resolution of 1 arcsec is required over the 30–100- μm range.

h) Observations of the submillimeter lines from expanding shells around late-type stars to obtain atomic and isotopic abundances and determine the processes of molecular chemistry in those stars. Resolution of 1–10 arcsec over a wavelength range of 100–1000 μm would be needed.

i) Observations of dust formation and evolution in mass outflow regions around late-type stars, with emphasis on the cool outer regions merging with the interstellar medium. Wavelengths of 5–200 μm would be

used, with only moderate angular resolution. However, to study the inner regions would require the use of interferometer techniques such as speckle or a second reflector.

j) Observations of velocity flows in late-type stars using submillimeter atomic and molecular lines. Spatial resolution of 1 arcsec and a wide range of wavelengths (100–800 μm – heterodyne) would be needed.

B. THE INTERSTELLAR MEDIUM

a) Studies of the physical state of the interstellar medium (ISM) around protostellar objects. High resolution spectroscopy of molecular and atomic transitions, such as CO (869, 650, 430 μm), CI (810, 370 μm), CII (157 μm), and H₂O (429 μm). These probes will measure the temperatures, densities, and chemistry of the gas (see also Stellar Evolution c, d).

b) Observation of CO, CI, CII, and H₂O emission from slowly collapsing protostellar clouds to reveal evolution of the clouds (see also Stellar Evolution c, d).

c) Observations of shocked gas by CO, OH, and H₂O spectroscopy. This would require heterodyne spectroscopy in the submillimeter range and Fabry-Perot or grating spectroscopy in the 50–300- μm range.

d) Measurements of the HD/H₂ ratio to study the deuterium abundance as a function of galactic radius. This would compare the $J = 3-2$, $2-1$, and $1-0$ transitions of HD at 37, 56, and 112 μm with the $J = 4-2$ transition of H₂ from warm gas in star-forming regions.

e) CII observations of tenuous atomic HI regions in external galaxies to measure gas-cooling rates.

f) Images of dust emission from star-forming regions to determine spatial distribution, temperature, and chemical composition of the dust material.

g) Measurements of O, S, N, Ne, and Ar abundances in HII regions, in our galaxy and others out to Virgo, by means of fine-structure lines.

h) Observations of hydrides and hydride ions of the carbon, nitrogen, and oxygen families, plus those for metal species (Mg, Na, Fe, Ca, Li, Cl, P, etc.) not yet detected. These measurements are considered crucial for interstellar chemistry.

i) Observations of CI fine-structure lines in external galaxies and in small-shocked regions in our galaxy.

j) Observations of dust-grain composition from 2–100 μm absorption-feature spectroscopy. Measurements of variation of grain/mantle effect, with galactic region.

k) Observations of highly ionized species (NIII, OIII, NeV, etc.) in planetary nebulae to determine abundances in material returning to the ISM.

l) Absorption spectroscopy at high resolution of circumstellar shells between 2–10 μm .

m) Spectroscopy of refractory molecules, e.g., MgO, FeO, CaO, SiC, PN, AlO, etc., in hot-shocked regions where they may be liberated from grains.

- n) Spectroscopic studies of shocked, hot regions in the 2–20 μm range.
- o) Chemistry studies of protosolar regions, to test for differences with respect to the general ISM.

C. SOLAR SYSTEM

- a) A complete, high-resolution spectral survey of the planetary bodies. This would augment the inventory of elements through the detection of new molecules; determine key isotope abundances; probe deep atmospheric levels; determine the bulk compositions of the atmospheres of Triton and Pluto.
- b) Map temperature structure, cloud cover, and constituent abundances across planetary disks at mid-level atmospheric depths. Also study the comae of comets. This uses intermediate spectral resolution of 1.0–0.1 cm^{-1} .
- c) As for b), but deep-level structures. This uses low spectral resolutions of 20.0–1.0 cm^{-1} .
- d) High-angular and spectral-resolution study of upper planetary atmospheres. Trace constituents studied. Measure Doppler velocities to determine local meteorology and circulation. Also studies of non-LTE effects in planetary atmospheres and comets.
- e) Total thermal-spectrum measurements of cool bodies such as Io, Europa, Uranus, Neptune, Pluto, cometary nuclei, etc.
- f) Search for Jupiter-size bodies around nearby stars out to 30 l.y.

D. EXTRAGALACTIC STUDIES

- a) Observations of continuum and line emission from galactic nuclei.
- b) Spectroscopic observation of faint galaxies at 1–4 μm to obtain red-shifts and strengths of metallic bands as a function of red-shift, in order to obtain information about galactic evolution.
- c) Far-IR spectroscopic studies of elemental abundances, heating, and cooling mechanisms in the ISM for galaxies out to $Z > 1$.
- d) Photometric studies at far-IR wavelengths out to $Z > 1$ to determine gas-to-dust ratios and far-IR luminosities.
- e) Studies of global patterns of star formation in spiral galaxies.
- f) Broadband imaging of regions with radio jets and lobes in order to study the spectral distribution of nonthermal emission in the far-IR.
- g) VLBI. LDR could form one element of the ground-space VLBI network. Projects include distance measurements to beyond the coma cluster.
- h) Sunyaev-Zeldovitch (see Cosmology).

i) Spectroscopy of quasars at 1–4 μm . This would provide a unique probe of gas clouds within 1–30 l.y. of the ionizing sources of these objects. For $Z > 3$ Balmer emission lines and many forbidden lines fall in the infrared.

E. COSMOLOGY

a) Faint galaxies at $Z > 4$. Light-bucket studies at high sensitivity reveal granularity of the sky galaxy background.

b) Small-scale 3 K background anisotropy and the Sunyaev-Zeldovitch effect. Submillimeter studies of fireball relic radiation reveal small-scale structure related to turbulence and galaxy formation. Sunyaev-Zeldovitch effect is best detected by LDR. It will measure distance to galaxy clusters, in combination with X-ray measurements of electron densities.

c) Brown dwarf searches in nearby regions may determine the number of brown dwarfs and place a limit to their contribution to the missing mass of galaxies.

d) Galaxy spectra (see Galaxies).

e) Measurements of galaxy dust content as a function of Z to determine evolution of galaxy metal abundance.

f) Comparison of CII line flux with starlight as a function of Z .

g) Search for Lyman α relic radiation after decoupling at far-IR wavelength.

APPENDIX C

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16. Abstract <p>The Science and Technology Workshop on the Large Deployable Reflector (LDR) convened on June 21–25, 1982 to discuss a large ambient-temperature, submillimeter/far-infrared telescope in space. This document summarizes the results of the scientists, who discussed the scientific rationale for the LDR and the overall technological requirements. The main scientific objectives include studies of the origins of planets, stars and galaxies, and of the ultimate fate of the universe.</p> <p>The envisioned studies require a telescope with a diameter of at least 20 m, diffraction-limited to wavelengths as short as 30–50 μm (~ 1 arcsec spatial resolution at 100 μm). In addition, light-bucket operation with 1 arcsec spatial resolution in the 2–4 μm wavelength region would be useful in studies of high-redshifted galaxies. Such a telescope would provide a large increase in spectroscopic sensitivity and spatial resolving power compared with existing or planned infrared telescopes.</p>					
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